# Notes

**Title: An Analysis of Zonal Electricity Pricing and Behavior in Ontario**

Summary:

The document provides a detailed statistical and visual analysis of electricity prices and demand across various zones in Ontario’s electricity market. Using IESO (Independent Electricity System Operator) data, the report explores the temporal and spatial characteristics of both Hourly Ontario Energy Prices (HOEP) and Zonal Demand.

Key insights include:

- Identification of zones with the highest price volatility.

- Comparison of real-time demand patterns between industrial and residential zones.

- Analysis of dispatch deviations and their implications on grid reliability.

- Discussion on the correlation between zonal price signals and actual load behavior.

The report incorporates line plots, histograms, and box plots to illustrate price distributions and demand variability. It also evaluates the impact of transmission constraints and outlines challenges in achieving zonal equity in pricing.

Conclusion:

The study emphasizes the need for more granular investment strategies in infrastructure and market reform, especially in zones exhibiting high volatility and mismatch between dispatch and actual demand. The findings are directly relevant to planning Smart Grid investments and enhancing operational resilience.

Usefulness:

Highly relevant to research subparts involving demand variability, price volatility, and dispatch deviation.

============================================================

**RELEVANT POINTS FOR STUDY: ZONAL ELECTRICITY ANALYSIS (ONTARIO)**

============================================================

-- Subpart 1: Demand Variability --

- The report presents hourly demand profiles for each Ontario zone, highlighting significant intra-day variability in urban zones (e.g., Toronto) and seasonal peaks in industrial zones (e.g., Northwest).

- Coefficient of Variation (CV) is implicitly observed through box plots and standard deviation measures of hourly demand data.

- Zones like East and Southwest show greater fluctuation in peak vs. off-peak demand, indicating operational stress potential.

-- Subpart 2: Price Volatility and Dispatch Deviations --

- Zones are ranked based on price volatility metrics using HOEP data (Hourly Ontario Energy Price).

- High standard deviation of prices was observed in less populated zones (e.g., Bruce, Northeast), often due to low demand and inflexible generation sources.

- Evidence of frequent price spikes and deviations between scheduled vs. real-time dispatch is discussed, particularly in the context of system constraints.

- Discussion includes “Non-Conformance” (NC) and “Out-of-Service Limits” (OSL) as dispatch deviation types influencing price volatility.

-- Subpart 3: Transmission Outages and System Stress --

- Though outages are not explicitly catalogued, the study discusses how transmission constraints (e.g., intertie limits, congestion) can create localized price islands and system instability.

- These bottlenecks exacerbate the mismatch between zonal demand and supply, stressing local infrastructure.

-- Main Research Question Relevance --

- The paper advocates for zone-specific investment priorities due to unequal operational conditions across Ontario.

- Recommends a composite index approach to better quantify “readiness” for grid modernization—aligning directly with Smart Grid Readiness Index.

- Highlights the policy challenge of aligning price signals with infrastructure capacity and reliability.

============================================================

UTILITY

============================================================

- Directly supports methods for analyzing demand variability and price volatility.

- Offers visualization examples (box plots, histograms) useful for your own data analysis.

- Strengthens rationale for using zonal granularity in smart grid planning and investment prioritization.

====================================================================

**SUMMARY: An Overview of the Operation of Ontario’s Electricity Market**

====================================================================

Authors: H. Zareipour, C.A. Cañizares, K. Bhattacharya (University of Waterloo)

Context:

The paper provides a comprehensive explanation of Ontario's electricity market structure, focusing on both operational and financial mechanisms. It highlights market design, pricing, dispatch algorithms, reserve markets, and interjurisdictional trading mechanisms.

----------------------------------------------------------

Key Points:

----------------------------------------------------------

1. Market Structure:

- Opened May 1, 2002, transitioning from a vertically integrated structure.

- Operated by the Independent Electricity Market Operator (IMO, now IESO).

- Includes energy and operating reserve markets + Financial Transmission Rights (FTR).

- Transmission regulated by Hydro One Inc., owned by the Ontario government.

2. Pricing and Dispatch:

- Hourly Ontario Energy Price (HOEP) is the key pricing metric, derived from 5-minute Market Clearing Prices (MCPs).

- Two stages of scheduling: pre-dispatch (advisory) and real-time (financially binding).

- Both constrained and unconstrained optimization algorithms are used.

3. Operating Reserves:

- Three classes: 10S (spinning), 10N (non-spinning), and 30R (30-minute).

- Paid via MCP-based settlement; 10S is the most expensive reserve type.

4. Demand and Volatility:

- Early years showed high price volatility and unstable demand.

- Price spikes influenced by demand inelasticity, weather, outages, and intertie failures.

5. Load and Generation Behavior:

- Most Ontario loads are non-dispatchable; most generators are dispatchable.

- Introduction of HADL (Hour-Ahead Dispatchable Load) and SGOL (Spare Generation On-Line) programs to improve flexibility and reliability.

6. Interjurisdictional Trading:

- Conducted through 12 interties with U.S. and Canadian provinces.

- Includes constraints like Net Interchange Schedule Limits (NISL) and Intertie Congestion Prices (ICP).

- Mechanisms like Intertie Offer Guarantee (IOG) and Congestion Management Settlement Credit (CMSC) ensure financial fairness.

7. Financial Market:

- FTR auctions offer limited congestion risk hedging for exports.

- Revenues depend on Transmission Rights Settlement Credit (TRSC).

- No day-ahead forward market yet implemented at time of study.

8. Uplift Charges:

- All operating and reliability costs recovered via uplift charges.

- Separated into hourly and monthly cost categories.

----------------------------------------------------------

**Relevance to Research**

----------------------------------------------------------

- \*\*Subpart 1 (Demand Variability)\*\*: Describes inelastic demand and load response mechanisms (HADL), useful for identifying variability and stability measures.

- \*\*Subpart 2 (Price Volatility)\*\*: Explains MCP/HOEP pricing, sources of volatility, and dispatch deviation handling (CMSC, congestion).

- \*\*Subpart 3 (Transmission/Infrastructure Stress)\*\*: Includes detailed mechanisms like intertie congestion, capacity limits, and SGOL program for infrastructure resilience.

- \*\*General/Methodological\*\*: DSPS algorithmic structure, zonal vs provincial pricing, and real-time market response modeling offer methodological grounding for Smart Grid Readiness Index.

**Summary: AWR Resilience Metric Framework**

1. Purpose:

- Introduces a multi-stage resilience assessment framework (AWR) for electric distribution systems.

- Helps utilities shift focus from reliability to resilience, especially under high-impact, low-frequency (HILF) events.

2. Core Concept:

- AWR = Anticipate, Withstand, Recover.

- Each phase is evaluated using a structured set of metrics, drawing on system attributes, event progression, and decision theory.

3. Anticipate Phase (Blue Sky):

- Enhances situational awareness and preparedness before an event.

- Static factors like weather vulnerabilities, crew readiness, sensing, and system hardening are assessed.

- Relevant for SGRI's focus on proactive capacity and infrastructure readiness.

4. Withstand Phase (Black Sky):

- Evaluates how well the system resists and absorbs impacts during an event.

- Includes power flow feasibility, generation availability, topological robustness, and critical load preservation.

- Strong relevance to operational stress indicators across Ontario zones.

5. Recover Phase (Grey Sky):

- Measures system’s ability to restore critical services after an event.

- Uses automation, topology reconfiguration, and rapid recovery metrics.

- Relevant to resilience improvement strategies and smart investment planning.

6. Methodology:

- Applies Analytical Hierarchy Process (AHP) and Weighted Sum Models (WSM) to compute resilience scores.

- Considers stakeholder elicitation and data fusion from power flow simulations and graph-theoretic models.

7. Case Study:

- Validated on an isolated Alaskan grid (Cordova).

- Demonstrates benefits of battery storage (BESS), early warning systems, and automated switching.

- Shows measurable gains in resilience when applying AWR-informed planning.

8. Planning & Investment Implications:

- Supports targeted resilience upgrades (e.g., BESS, reclosers).

- Facilitates informed prioritization across anticipate, withstand, and recover domains.

- Aligns directly with your goal of strategic investment using a Smart Grid Readiness Index.

9. Operational Insights:

- Allows utilities to simulate and select optimal proactive/reactive control actions.

- Enables grid operators to track performance evolution through the AWR lifecycle.

10. Key Formulas:

- RA (Anticipate Score) = Weighted domain scores from threats, loads, and recovery domains.

- Rw (Withstand Score) = AHP-derived vector from generation, load, topological metrics.

- RR (Recover Score) = Computed from restoration speed, system reconfigurability, etc.

Conclusion:

The AWR framework provides a practical, stage-aware resilience metric system that is highly adaptable and supports both planning and real-time operation. It is directly applicable for evaluating zone-specific grid stress and guiding smart investment decisions in Ontario’s electricity zones.

====================================================================

**RELEVANT POINTS FOR STUDY: AWR RESILIENCE METRIC FRAMEWORK**

====================================================================

-- Subpart 1: Demand Variability (Operational Stress) --

- The AWR framework identifies system stress in the “Withstand” phase, which includes metrics for load flexibility, critical load preservation, and distributed energy availability.

- Variability in demand is accounted for through modeling scenarios of load failure and system overload.

-- Subpart 2: Price Volatility and Dispatch Deviations --

- Although not focused on market prices, the AWR model simulates power flow disruptions and dispatch constraints during HILF events.

- Dispatch capacity and deviation under stressed grid states are measured using power feasibility and topology sensitivity—these relate indirectly to mismatch behavior in zonal operations.

-- Subpart 3: Infrastructure Stress and Transmission Outages --

- Transmission fragility is integrated via topology metrics in the “Withstand” and “Recover” phases.

- “Recover” metrics include restoration speed, sectionalizing capability, and reconfigurability—all critical to assessing zone-specific infrastructure resilience.

-- Smart Grid Readiness Index (SGRI) Relevance --

- AWR provides a tiered scoring system (Anticipate, Withstand, Recover) that can inform composite index construction.

- The weighting scheme (via AHP and WSM) mirrors multi-criteria decision-making (MCDM) used in your index framework.

- The metric structure encourages prioritizing zones with low resilience scores for smart grid upgrades (e.g., BESS, automation, monitoring).

-- Methodological Support --

- Applies stakeholder-driven scoring + technical modeling.

- Uses graph theory + power flow + control flexibility = methodological bridge to your zonal stress and investment prioritization goals.

- Enables simulation of investment impact over time (e.g., adding reclosers or BESS increases recovery scores).

====================================================================

UTILITY

====================================================================

- AWR's modular metric structure can be adapted to Ontario zones as part of SGRI.

- Provides meaningful classification of resilience as a dimension beyond raw demand/price data.

- Supports visual and quantitative dashboards for zone-level planning.

- Bridges physical grid performance with strategic prioritization.

Recommendation:

Incorporate AWR scoring logic and recovery time metrics into the SGRI formulation. Use “Withstand” and “Recover” scores to augment infrastructure and control readiness scores per zone.

===================================================================

**SUMMARY: Cybersecurity and Electrical Power Systems**

===================================================================

Author(s): Not specified

Content Type: Review + Framework Design

Summary:

This document provides a comprehensive review of cybersecurity challenges, vulnerabilities, and mitigation strategies in modern electrical power systems. It focuses on how the integration of ICT (Information and Communication Technologies), Smart Grids, and IoT-based control infrastructure introduces both opportunities and new security threats across the grid's physical and cyber layers.

The paper outlines:

- Threat types (DoS, spoofing, malware, etc.)

- Vulnerabilities in SCADA, AMI, DER, and PMU components

- Defense mechanisms such as firewalls, anomaly detection, encryption, and AI-driven control

- Cybersecurity frameworks such as NIST, IEC 62351, and IEC 61850

- Real-world case studies (e.g., Ukraine blackout)

- Strategic recommendations for integrating cyber-resilience into operational planning

===================================================================

**RELEVANT POINTS FOR STUDY: SMART GRID READINESS + ZONAL STRESS**

===================================================================

-- Subpart 1: Demand Variability --

- No direct coverage; however, mentions how compromised AMI (Advanced Metering Infrastructure) could distort demand readings or cause falsified peak events.

-- Subpart 2: Price Volatility and Dispatch Deviations --

- Highlights how manipulation of real-time data (via compromised PMUs or SCADA) can lead to incorrect price signals and grid instability.

- SCADA system vulnerabilities can cause mismatches between scheduled and actual dispatch, aligning directly with your deviation metrics.

-- Subpart 3: Infrastructure Reliability / Transmission Stress --

- Strong relevance: emphasizes how physical grid resilience must include cyber-physical system protection.

- Cyberattacks on substations or DERs can mimic outage conditions and increase stress on backup infrastructure.

- Points out that inadequate security increases the frequency and severity of unplanned outages.

-- Smart Grid Readiness Index Relevance --

- Cybersecurity maturity (e.g., use of intrusion detection systems, encryption standards) should be part of the composite readiness score.

- Zone-specific cyber exposure could be mapped using:

• density of PMUs/DERs,

• interconnection protocols,

• SCADA deployment scale.

-- Methodological Additions --

- Recommends integration of cybersecurity posture assessment in infrastructure planning.

- Suggests machine learning and behavior-based anomaly detection to support dynamic response capabilities.

===================================================================

UTILITY

===================================================================

- Enhances your SGRI by adding a "Cyber Readiness" dimension to reflect vulnerability and preparedness.

- Connects digital layer threats to operational deviations, relevant for risk modeling per Ontario zone.

- Justifies investment prioritization in zones with critical control systems and weak security coverage.

Recommendation:

Use this document to define metrics or qualitative ratings for cybersecurity posture at the zonal level within your Smart Grid Readiness Index. Tie it to control reliability and data integrity impact on dispatch operations.

====================================================================

**SUMMARY: Data-Driven Next-Generation Smart Grid – Review Paper**

====================================================================

Type: Review Article

Focus: Comprehensive overview of technologies, data models, and frameworks shaping the future of smart grid systems.

Overview:

This review explores data-centric architectures for next-generation smart grids. It identifies enabling technologies, key data sources, communication protocols, and decision-making models that underpin a sustainable, responsive, and intelligent power grid.

Key areas covered:

- Smart metering infrastructure (AMI)

- Communication networks (IoT, 5G, LPWAN)

- Data analytics: forecasting, anomaly detection, optimization

- Cybersecurity models

- Renewable energy integration (solar, wind, EVs)

- Edge computing and cloud platforms

- Machine Learning (ML) and Artificial Intelligence (AI) applications

====================================================================

**RELEVANT POINTS FOR SGRI STUDY**

====================================================================

-- Subpart 1: Demand Variability --

- Uses advanced ML algorithms (LSTM, RNN, CNN) for short-term load forecasting.

- Highlights the importance of real-time metering (AMI) and edge computing for capturing demand fluctuations.

- Suggests zonal demand modeling using historical smart meter data, aligning directly with your intra-day/inter-day CV calculations.

-- Subpart 2: Price Volatility and Dispatch Deviations --

- Discusses how predictive analytics and AI can anticipate demand-supply mismatches.

- Describes market-based dispatch models that adjust in real-time based on multi-variable input (weather, load, price signals).

- Emphasizes demand response mechanisms as a stabilizing tool to reduce dispatch deviation risk.

-- Subpart 3: Infrastructure and Grid Stress --

- Details how DERs (Distributed Energy Resources), microgrids, and storage units support resilience in high-stress conditions.

- Advocates grid segmentation and control strategies to localize and mitigate outages—relevant to outage impact analysis.

-- Smart Grid Readiness Index Relevance --

- Strong alignment with index construction using:

• Smart meter penetration

• Real-time analytics capabilities

• DER deployment

• Forecasting accuracy

• Demand response flexibility

- Recommends a layered approach to readiness, considering both technological maturity and integration depth.

-- Methodological Insights --

- Proposes a three-tiered architecture:

1. Data acquisition layer (sensors, AMI)

2. Network and communication layer

3. Intelligence and control layer (AI/ML engines)

- Encourages scenario-based simulations to test grid behavior under peak load or attack scenarios.

====================================================================

UTILITY FOR YOUR PROJECT

====================================================================

- Can inform your SGRI scoring rubrics: forecastability, control autonomy, data visibility.

- Provides data categories and methods for zoning Ontario by digital maturity.

- Supports justification for investments in metering, edge/cloud analytics, and AI for high-volatility zones.

Recommendation:

Use this document to define data-driven capabilities as a readiness pillar within your Smart Grid Readiness Index. Pair with zonal metrics (AMI density, forecast error, DER saturation) to score readiness in Ontario zones.

**Summary: Day-Ahead Congestion Management in Distribution Systems Through Household Demand Response and Distribution Congestion Prices**

--------------------------------------------------------------------------------------------------------

Authors: Weijia Liu, Qiuwei Wu, Fushuan Wen, Jacob Østergaard

Published in: IEEE Transactions on Smart Grid, Vol. 5, No. 6, Nov 2014

Overview:

This paper proposes a Distribution Congestion Price (DCP)-based market mechanism to manage congestion in electric distribution systems by leveraging household demand response (DR) in the day-ahead market. The mechanism is aligned with the NordPool Spot market framework and targets small-scale energy consumers with flexible appliances.

Key Contributions:

- Introduces DCPs derived from Locational Marginal Pricing (LMP) to influence household energy consumption behavior.

- Models flexible demand from household appliances (e.g., heat pumps, refrigerators).

- Utilizes aggregators as intermediaries to manage demand schedules on behalf of households.

- Demonstrates how DCPs can shift load to avoid congestion while maintaining comfort levels.

- Provides an AC Optimal Power Flow (ACOPF)-based optimization framework to compute DCPs.

- Validates approach via case studies using a Danish 60kV/10.5kV distribution system.

**Relevant Points for Your Study:**

- Zonal Congestion Analysis: DCPs provide a fine-grained, node-level congestion signal which can help assess which zones face the greatest operational stress—aligning with your goal of identifying stressed Ontario zones.

- Dispatch Mismatch & Price Volatility: The link between predicted day-ahead market prices and real-time congestion highlights the mismatch problem, relevant to your Subpart 2 research on dispatch deviation.

- Smart Grid Readiness: The framework implies the need for advanced DR infrastructure, market communication, and optimization—key components in Smart Grid Readiness Index criteria.

- Methodological Support: The ACOPF modeling and use of DR optimization support your methodological section for modeling price/demand interplay and flexible planning.

- Practical Validation: Results show DCPs reduce congestion by shifting loads, which supports your intent to prioritize investments in zones where such mechanisms could be effective.

Applications:

- Offers a blueprint for integrating demand-side flexibility into congestion pricing mechanisms.

- Suggests how Ontario zones with high flexible demand potential could use similar pricing strategies to enhance grid performance.

- Supports formulation of metrics tied to congestion frequency and DR capacity in readiness index computation.

**SUMMARY: Electricity Consumption Clustering Using Smart Meter Data**

------------------------------------------------------------------

Authors: Alexander Tureczek, Per Sieverts Nielsen, Henrik Madsen

Published in: Energies, Vol. 11, 2018, Article 859

GOAL:

This study proposes preprocessing techniques to improve the performance of K-Means clustering on smart meter data by accounting for temporal features (autocorrelation and wavelets), enabling better classification of domestic electricity consumption patterns.

KEY METHODOLOGY:

- Input: Hourly smart meter data for 32,241 households in Esbjerg, Denmark over one week.

- Preprocessing: Removal of missing/erroneous values, normalization, extraction of autocorrelation features, and wavelet transformation.

- Clustering: Used K-Means with statistical validation (MIA, CDI, DBI, Silhouette index) and unsupervised cross-validation.

- Autocorrelation Feature Extraction outperformed simple normalization and wavelet approaches in identifying distinct consumer clusters.

**RELEVANT POINTS FOR YOUR STUDY:**

---------------------------------

-- Subpart 1: Demand Variability --

✓ Demonstrates that residential demand has temporal structure which standard clustering methods ignore.

✓ Introduces feature engineering (autocorrelation lags) to uncover hidden demand variation across households.

✓ Distinguishes households into 12 meaningful subgroups based on recurring usage cycles, not just peak magnitude.

✓ Suggests methodology for analyzing intra-day and inter-day load patterns using K-Means + time-series features.

-- Methodological Relevance --

✓ Provides a robust and scalable way to cluster large-scale hourly consumption data.

✓ Uses multiple cluster validation metrics to ensure clustering stability and quality.

✓ Feature extraction using autocorrelation can be adapted for Ontario zones to reveal volatile load segments.

-- Potential Integration in SGRI --

✓ Cluster membership can act as a volatility or load diversity index.

✓ Helps classify Ontario zones by consumer behavior patterns (peakiness, regularity).

✓ Insights can feed into demand-side readiness indicators within Smart Grid Readiness Index.

-- Additional Notes --

✓ Demonstrates that preprocessing is crucial—normal K-Means fails on raw or normalized data due to temporal blindness.

✓ Cluster composition analysis (by dwelling type and postal code) confirms clustering captures usage behavior rather than geography or infrastructure.

RECOMMENDATION:

Use the autocorrelation-based clustering approach described in this paper to identify consumer-level variability in Ontario zones. Aggregate clustering results to generate a zonal load variability index (ZLVI) as part of the operational stress metric.

**Summary of "Electricity Price Forecasting for Operational Scheduling of Behind-the-Meter Storage Systems":**

Authors: Hamed Chitsaz, Payam Zamani-Dehkordi, Hamidreza Zareipour, Palak P. Parikh

Core Idea:

The paper presents a new electricity price forecasting strategy specifically designed for optimizing the operation of behind-the-meter (BTM) battery energy storage systems (BESS) in real-time electricity markets using high-resolution market data.

Key Contributions:

1. \*\*Forecasting Strategy\*\*: An intra-hour rolling horizon (IRH) approach combines two forecasting models:

- \*\*High-resolution model (MHR)\*\* uses 5-minute market clearing prices (MCPs) for near-term (1-hour-ahead) predictions.

- \*\*Low-resolution model (MLR)\*\* provides multi-hour forecasts using hourly data.

2. \*\*Statistical Insights\*\*:

- Proposed method outperforms Ontario IESO’s Pre-Dispatch Price (PDP) forecasts.

- Average MAE reduced from $9.02/MWh (PDP) to $7.24–$5.56/MWh using 1–6 MCPs.

3. \*\*Economic Evaluation\*\*:

- Implementing this forecast for a 500 kW BESS resulted in 62% of possible energy arbitrage savings versus 43% with PDP.

- Optimal strategy includes only one MCP per hour, balancing forecast accuracy and real-time utility.

4. \*\*Practical Relevance for Ontario\*\*:

- Real Ontario electricity price data used to validate the forecasting models.

- Shows applicability of short-term price forecasts to enhance dispatch decisions.

**Relevant Points for Your Study on Smart Grid Readiness in Ontario:**

- Highlights importance of \*\*high-resolution price data\*\* for \*\*real-time dispatch accuracy\*\*—key for evaluating zone-level operational stress.

- Provides a \*\*robust model for forecasting and BESS scheduling\*\*—relevant to Smart Grid planning and investment prioritization.

- Reveals \*\*volatility patterns and prediction challenges in Ontario's market\*\*, directly linking to your subpart on \*\*price volatility and dispatch deviation\*\*.

- Suggests \*\*forecasting performance should be judged by economic impact\*\*, not just error metrics—important for cost-benefit analyses in Smart Grid investments.

Citation:

H. Chitsaz, P. Zamani-Dehkordi, H. Zareipour, and P. P. Parikh, “Electricity Price Forecasting for Operational Scheduling of Behind-the-Meter Storage Systems,” \*IEEE Trans. Smart Grid\*, vol. 9, no. 6, pp. 6612–6622, Nov. 2018. doi:10.1109/TSG.2017.2717282

**Summary of Document: Electricity Demand Forecasting for Decentralised Energy Management**

This paper presents a novel, lightweight methodology for electricity demand forecasting aimed at decentralised energy systems, particularly for grid-edge and islanded networks lacking real-time data. The proposed method involves:

- \*\*Lumped Model Approach\*\*: Aggregated forecasting without requiring high-resolution real-time data.

- \*\*Time Series Analysis\*\*: Use of historical electricity demand data from the UK National Grid (2005–2019).

- \*\*Dimensionality Reduction\*\*: Piecewise Aggregate Approximation (PAA) to reduce data complexity while preserving patterns.

- \*\*Piecewise Interpolation\*\*: Smoothing through cubic polynomial segments for more accurate forecasting.

- \*\*Symbolic Approximation\*\*: Optional use of SAX (Symbolic Aggregate approXimation) to further compress the data into binary representations.

- \*\*Forecast Horizon\*\*: Designed for 4-hour forecasts, extendable to 1–12 months.

- \*\*Performance Evaluation\*\*: Benchmarked against Naïve2 and Holt-Winters methods, achieving R² > 0.92 average.

- \*\*Advantages\*\*: Works well without continuous training or real-time data, making it suitable for decentralized networks.

**Relevant Points for Your Study:**

1. \*\*Supports Subpart 1 (Demand Variability)\*\*:

- Demonstrates daily, weekly, and monthly patterns in electricity demand.

- Uses clustering and dimensionality reduction—aligns with your plan to calculate variability metrics like Coefficient of Variation (CV).

- Applicable to Ontario’s zones using smart meter or zonal demand data.

2. \*\*Cross-Cutting Methodological Support\*\*:

- Introduces forecasting methods (PAA, cubic interpolation, SAX) that are computationally lightweight—helpful for rural or under-instrumented zones.

- Offers baseline accuracy metrics (RMSE, MAE, R²) for demand forecasts you can compare with Ontario’s zone-specific data.

- Framework could guide how to build your Smart Grid Readiness Index using forecast reliability or predictability as one of the dimensions.

3. \*\*Decentralized Grid Application\*\*:

- Ideal for contexts without centralized dispatch or dense instrumentation—e.g., northern or rural Ontario zones.

4. \*\*Relevance to Smart Grid Investment Planning\*\*:

- Supports adaptive load shifting and proactive control, useful in framing investment strategies that align with load predictability.

Recommendation:

This paper is highly relevant for methodological grounding and supports both demand-side analysis and smart grid planning in decentralized contexts.

**Summary: Achieving Electricity Grid Resiliency (Centre for Urban Energy, Ryerson University)**

This white paper addresses the growing concern of electricity grid resilience in Ontario, especially in light of climate change and increasing severe weather events. It emphasizes a systems-level approach to improving grid resiliency, distinguishing it from reliability, and offers practical frameworks, metrics, and policy suggestions to bolster the electricity infrastructure against future disruptions.

Key Concepts:

- \*\*Resilience vs. Reliability\*\*: Reliability measures performance under normal conditions; resilience measures capacity to absorb, recover from, and adapt to extreme events.

- \*\*Vulnerabilities Identified\*\*:

- Ageing infrastructure

- High-rise dependency without backup

- Centralized generation risk

- Interdependency with critical infrastructure (e.g. telecom, transport)

- Climate change-induced weather extremes (ice storms, floods, heatwaves)

Metrics for Resilience (proposed):

- % of customers affected (overhead/underground, critical facilities)

- Restoration times for 50%, 80%, and 100% recovery

- Average outage duration by infrastructure type

- Resilience checklist and post-event performance review (PEEI spreadsheet)

Recommended Measures:

- Asset hardening and smart technologies (self-healing grids)

- Smart grid expansion for adaptability and flexibility

- Distributed generation and microgrids

- Risk-based planning using extreme weather models

- Policy integration between city planning and utility operations

Case Applications:

- Toronto-specific weather modeling (1 km² resolution)

- Review of major weather events (2013 ice storm, 2012 hurricane Sandy)

- Suggested indicators for local Distribution Companies (LDCs) and policymakers

**Relevant Points for Your Study:**

1. \*\*For Subpart 3 — Transmission Outages\*\*:

- Proposes concrete resilience indicators tied to outage frequency, duration, and infrastructure type.

- Offers a structured methodology to link extreme weather to service disruption and recovery profiles.

2. \*\*Cross-Cutting — Smart Grid Readiness Index\*\*:

- Framework to evaluate resilience across temporal stages: before, during, and after events.

- Suggests metrics suitable for inclusion in a composite Smart Grid Readiness Index.

3. \*\*Operational Stress and Vulnerability Mapping\*\*:

- Supports integration of climate projections into zonal grid stress assessments.

- Advises local utilities to use post-event data for system adaptation — useful for correlating with your dispatch deviation analysis.

4. \*\*Strategic Investment Guidance\*\*:

- Links resilience planning with economic and policy feasibility — directly informs prioritization in your investment strategy.

Conclusion:

The report is highly applicable to your Smart Grid Readiness research, especially for structuring outage-based resilience metrics and aligning policy recommendations with technical indicators.

**SUMMARY: IESO-GIF Projects Evaluation Report 2024**

Publisher: Independent Electricity System Operator (IESO)

Type: Government/Agency Evaluation Report

Focus: Assessment of Smart Grid Fund (SGF) and Grid Innovation Fund (GIF) pilot projects across Ontario.

Key Themes:

- The report evaluates 83 projects funded under SGF and GIF between 2011 and 2023.

- Projects are grouped into categories: demand response, energy storage, microgrids, DER integration, EV charging, and data analytics.

- Emphasis is placed on replicability, scalability, customer benefit, operational integration, and innovation value.

Findings:

- \*\*Impact on Grid Resilience\*\*: Projects improved system flexibility and reduced peak load pressure.

- \*\*Innovation Outcomes\*\*: AI-based DER coordination and transactive energy platforms were successfully piloted.

- \*\*Regional Gaps\*\*: Adoption uneven across zones; rural and northern areas lag in deployments.

- \*\*Data Use\*\*: Strong focus on data-driven tools for load forecasting, asset management, and outage prediction.

- \*\*Customer Engagement\*\*: Projects involving behavioral DR and real-time feedback led to higher demand shifting.

Key Metrics Used:

- Load shifted (kWh)

- Peak reduction (%)

- Storage performance (round-trip efficiency, response time)

- DER controllability and dispatchability

- Scalability potential by zone

---------------------------------------------------------------

**RELEVANT POINTS FOR SMART GRID READINESS INDEX (SGRI) STUDY**

---------------------------------------------------------------

-- Main Research Question (Zone Readiness + Investment Prioritization) --

✓ Offers empirical basis for assessing which Ontario zones have received innovation investments.

✓ Project outcomes reveal gaps in Smart Grid deployment — useful for readiness scoring.

✓ Prioritizes scalability and replicability — alignable with index criteria.

-- Subpart 1: Demand Variability --

✓ DR pilots in various zones directly address demand smoothing.

✓ Data-driven feedback systems and AI-based control tested in demand-variable zones.

-- Subpart 2: Price Volatility & Dispatch Deviation --

✓ Some pilots tested real-time DER dispatch platforms; relevant to price-responsiveness metrics.

✓ Data analytics platforms contributed to better operational decision-making.

-- Subpart 3: Infrastructure Resilience --

✓ Microgrid and storage projects evaluated based on contribution to outage mitigation.

✓ Performance metrics (storage reliability, fast dispatch, recovery time) support outage-based scoring.

-- Cross-Cutting Support --

✓ Provides zone-wise innovation adoption insights (north, rural = low adoption).

✓ Highlights which zones could benefit most from future investment — key to your strategic investment aim.

✓ Lists technical and engagement KPIs that can be incorporated into SGRI scoring rubrics.

Recommendation:

Use this report as a validation dataset to map innovation maturity across Ontario zones and to define benchmarks for smart grid technology penetration, demand response capacity, and DER controllability in your index formulation.

**SUMMARY: Integration of Renewables into the Ontario Electricity System**

Authors: Brian Rivard and Adonis Yatchew

Published in: The Energy Journal, Vol. 37, SI2 (2016)

FOCUS:

The paper evaluates Ontario’s aggressive renewable integration (mainly wind) into its hybrid electricity market. It examines price impacts (merit-order effect), operational integration, procurement structures, and policy recommendations for efficiency.

KEY POINTS:

— Market Structure & Renewable Policy —

- Ontario operates a "hybrid market": competitive wholesale pricing + government-directed long-term procurement.

- Most generation is secured via long-term contracts (e.g., FITs).

- Since 2009, renewable capacity (esp. wind) has expanded rapidly while coal has been phased out.

- The result: market price (HOEP) has declined, but overall “all-in price” has risen (60 → 100 CAD/MWh).

— Price Dynamics & Merit-Order Effect —

- Wind generation has a strong merit-order effect: 500 MW → 1500 MW of wind reduces HOEP by ~7 CAD/MWh.

- Negative prices increased after wind dispatch introduction (post-2013), tied to high renewable output and low demand.

- Wind output correlated negatively with demand until 2013; positive but weak thereafter.

— Operational Integration —

- IESO introduced 5-minute dispatch, centralized forecasting for wind, and compliance mechanisms.

- Dispatch flexibility limited during surplus baseload events, causing “constrained off” of nuclear/hydro resources.

- Wind required to submit telemetry + static plant data; receives congestion payments when curtailed.

— Procurement Process: Critique —

- Highly centralized procurement via “ministerial directives” undermines market efficiency.

- Authors advocate for subsidiarity (decentralized decision-making) and clearer separation between policy and regulation.

- Auditor General of Ontario flagged overpayment and inefficiency in FIT-based procurement (~$257/tonne CO₂).

— Decarbonization Outcomes —

- GHGs reduced from 35 to <7 megatonnes (2005–2014).

- But abatement costs high, and renewables often displaced other carbon-free sources like nuclear during off-peak.

---------------------------------------------------------------

**RELEVANT POINTS FOR YOUR SMART GRID READINESS STUDY**

---------------------------------------------------------------

-- MAIN RESEARCH QUESTION (Readiness + Strategic Investment) --

✓ Shows zone-agnostic investment practices; centralized control = uneven impact across regions.

✓ Reveals systemic integration success but financial inefficiency → can motivate readiness index that corrects such gaps.

✓ Demonstrates need for decentralized, data-driven frameworks that SGRI can embody.

-- SUBPART 1: Demand Variability --

✓ Detailed load patterns: summer/winter peaks, 24–12 hour cycles; supports temporal demand stress analysis.

✓ Demand decline since 2005 supports trend segmentation in your CV analysis for variability.

-- SUBPART 2: Price Volatility & Dispatch Deviation --

✓ Provides statistical model linking renewable input (wind, hydro) to real-time price volatility.

✓ Correlation analyses (e.g., wind–demand = –0.1 to 0.2) can inform zonal mismatch indicators.

✓ Supply-demand curve effects show nonlinear price response—ideal for price sensitivity layer of SGRI.

-- SUBPART 3: Infrastructure Resilience --

✓ High renewable penetration exacerbated surplus baseload events, often requiring curtailments.

✓ Centralized IESO interventions (e.g., wind dispatch floors, forecast modeling) show grid adaptation stress.

✓ Congestion and CMSC credits signal zones with frequent control interventions—quantifiable via SGRI.

-- CROSS-CUTTING (Methodology & Market) --

✓ Market operation models (HOEP, MCP, CMSC) offer parameters for integration into readiness scoring.

✓ Case for market-based procurement aligns with prioritization through composite SGRI rather than directives.

✓ Extensive IESO data access encourages reproducible and scalable zonal evaluations.

RECOMMENDATION:

This paper provides deep methodological and empirical support for incorporating merit-order effects, dispatch adjustments, and centralized vs. decentralized investment indicators into your Smart Grid Readiness Index and strategic investment prioritization model.

**SUMMARY: Multicriteria Support for the Evaluation of Electricity Supply**

Authors: M. Cinelli, W. Harasymowicz-Birnbach, P. Komendantova, L. Giarola, A. Spada, A. Tzachor, V. Vinciarelli, D. Zakeri, and A. Hawkes

Published in: Renewable and Sustainable Energy Reviews, Vol. 157, 2022

Overview:

This paper proposes a multicriteria decision analysis (MCDA) framework for evaluating electricity supply systems using multiple dimensions: technical, economic, environmental, and social. It highlights the need for balancing trade-offs in investment decision-making and emphasizes structured approaches to stakeholder engagement.

Key Contributions:

- Presents a modular MCDA framework applicable across national and subnational contexts.

- Applies to both centralized and decentralized supply systems.

- Highlights how to weigh and rank electricity supply alternatives based on diverse criteria.

- Uses real-world case studies to illustrate deployment.

Framework Components:

- \*\*Criteria Categories\*\*:

• Technical (efficiency, reliability)

• Economic (CAPEX, OPEX, cost-effectiveness)

• Environmental (GHG emissions, land use)

• Social (public acceptance, employment, equity)

- \*\*Methods Used\*\*:

• AHP (Analytic Hierarchy Process)

• PROMETHEE, TOPSIS, ELECTRE

• Sensitivity analysis and stakeholder elicitation

---------------------------------------------------------------

**RELEVANT POINTS FOR SMART GRID READINESS INDEX STUDY**

---------------------------------------------------------------

-- Main Research Question (Investment Prioritization & Readiness) --

✓ MCDA provides a validated way to structure investment decisions across competing zones.

✓ Allows inclusion of technical-operational stress indicators and qualitative factors (resilience, equity).

✓ Useful to identify zones with the most favorable readiness-to-impact ratio.

-- Cross-Cutting Support (Methodology) --

✓ Demonstrates how to combine quantitative and qualitative data into a composite score — central to your Smart Grid Readiness Index (SGRI).

✓ Suggests sensitivity analysis to test robustness of zonal rankings under different investment scenarios.

✓ Offers weighting schemes for indicators (demand variability, price volatility, outage resilience) based on expert/stakeholder input.

-- Subpart 3: Infrastructure Stress & Social Considerations --

✓ Social criteria such as regional equity, affordability, and acceptance can be integrated into zone-level scoring to identify vulnerable areas.

✓ Supports inclusion of social readiness or impact-per-dollar as part of investment prioritization.

-- Tools & Techniques --

✓ Recommends tools (e.g., AHP + TOPSIS) that are open-source or computationally lightweight.

✓ Provides transparency in indicator selection, scoring, and aggregation — ideal for academic and policy use.

RECOMMENDATION:

Use the MCDA structure outlined in this paper to design your Smart Grid Readiness Index scoring framework. Adapt the weighting and criteria hierarchy to reflect your study’s focus on zonal operational stress, infrastructure resilience, and investment potential across Ontario.

**Summary: Operational Planning Strategies to Mitigate Price Uncertainty in Day-Ahead Market for a Battery Energy System**

Authors: Ahmed Mohamed, Rémy Rigo-Mariani, Vincent Debusschere, Lionel Pin

Published: IEEE Access, June 2024

Main Focus:

The paper proposes explainable and practical operational planning strategies for Battery Energy Storage Systems (BESS) to participate profitably in Day-Ahead (DA) electricity markets under price uncertainty.

Key Contributions:

- Introduction of two methods to generate price scenarios using Geometric Brownian Motion (GBM):

- Method A: Combines SARIMA forecasts with GBM.

- Method B: Uses residuals from previous days to simulate volatility.

- Comparison of five BESS bidding strategies against two baselines:

- Deterministic backcasting.

- Stochastic optimization using Sample Average Approximation (SAA).

- Performance evaluated by comparing actual profits to a perfect forecast benchmark.

- Sensitivity analysis explores the effect of forecast quality and number of price scenarios on BESS profit.

**Relevant Points for Your Study:**

- Directly supports your Subpart 2 (price volatility and dispatch mismatches) with real-world strategies to handle DA market uncertainty.

- GBM-based scenario generation offers an alternative to traditional Monte Carlo and ARIMA models—valuable for data-scarce zones in Ontario.

- Emphasizes the importance of selecting a single BESS schedule after evaluating profit outcomes—a good practice for Smart Grid Readiness Index construction.

- Demonstrates that even simple methods (e.g., Method B) using historical residuals can outperform traditional models under certain forecast error conditions.

- Offers a framework for benchmarking economic viability across zones when considering storage investments.

Application in Smart Grid Readiness:

- Provides a methodology to link forecast accuracy, scenario-based optimization, and profit realization—a potential metric for operational readiness.

- You could adapt the SARIMA+GBM-based strategies to model Ontario zonal dispatch errors or price response precision.

- Profit loss due to forecast uncertainty could be a component in your Smart Grid Readiness Index to evaluate market alignment or economic risk.

Conclusion:

This paper is a strong methodological reference for price uncertainty modeling, scenario simulation, and storage-based bidding evaluation—critical elements for grid investment planning and resilience assessment in Ontario's electricity zones.

**Summary of "Real-Time Pricing Control on Generation-Side: Optimal Demand-Tracking Model and Information Fusion Estimation Solver" (IEEE Transactions on Power Systems, 2014)**

This paper introduces an Information Fusion based Pricing Control (IFPC) strategy for real-time pricing on the generation side in liberalized electricity markets. The objective is to achieve dynamic supply-demand matching by adjusting nodal prices through a feedback control system operated by the Independent System Operator (ISO).

Key Concepts and Contributions:

- The IFPC scheme enables ISO to propose nodal prices based on forecast demand and wind power generation, which GenCOs respond to by adjusting generation to maximize profit.

- A quadratic optimal tracking problem is formulated with constraints like power balance, price stability, and line flow ratings.

- The novelty lies in the use of information fusion estimation techniques for computing price signals using multi-source inputs over a receding preview horizon.

- The paper verifies effectiveness using the IEEE 118-bus test system, considering thermal and wind generation under varying line constraints and forecast uncertainties.

- Comparative analysis with Negotiated Predictive Dispatch (NPD) shows IFPC provides better supply-demand balance and lower total generation cost, albeit with longer computation time.

**Relevant Points for Study:**

- IFPC is highly relevant for studying price volatility and dispatch deviations (Subpart 2).

- Demonstrates how real-time pricing can incentivize GenCOs to respond to demand and renewable fluctuation, enhancing grid flexibility and profitability.

- Shows how ISO can integrate demand forecasts, GenCO dynamics, and system constraints to derive equilibrium price strategies.

- Case studies reveal IFPC's robustness under wind power uncertainties and transmission congestion.

- Useful for understanding coordination mechanisms between ISO and GenCOs in smart grid environments.

Potential Applications in Your Research:

- Model IFPC to simulate price responses and dispatch deviations across zones.

- Use insights on PTU time and flow constraints to identify stress-prone zones.

- Extend the methodology to Ontario's zonal structure for demand-forecast-response modeling.

**SUMMARY: Data-Driven Probabilistic Machine Learning in Smart Grid Systems**

Published in: Renewable and Sustainable Energy Reviews, 2022

Authors: Mohammad Reza Hesami, Amir Safari, Reza Fadaeenejad, et al.

Main Focus:

The paper surveys the landscape of probabilistic machine learning (ML) methods applied to smart grid systems. It highlights the importance of uncertainty modeling, data-driven decision-making, and real-time adaptive control. The review spans forecasting, anomaly detection, load disaggregation, energy optimization, and cyber-physical resilience.

Key Contributions:

- \*\*Uncertainty Quantification\*\*: Emphasizes the role of probabilistic forecasting over point forecasts in smart grid operations.

- \*\*Probabilistic ML Models\*\*: Includes Bayesian networks, Gaussian processes, ensemble methods, and deep generative models (e.g., variational autoencoders).

- \*\*Applications Reviewed\*\*:

• Short-term load and price forecasting

• PV/wind power uncertainty modeling

• Anomaly and fault detection in AMI and SCADA

• Cybersecurity and intrusion detection

- \*\*Benchmarking Criteria\*\*: Accuracy, interpretability, computational cost, and data requirements.

- \*\*Framework Proposed\*\*: A layered architecture with data acquisition, preprocessing, model training, and deployment phases, applicable to distributed grid environments.

**Relevant Points for Your Smart Grid Readiness Index (SGRI) Study:**

------------------------------------------------------------------------

-- Subpart 1: Demand Variability --

✓ Probabilistic load forecasting methods help model intra- and inter-day variability.

✓ Emphasizes temporal granularity (15-min, hourly) and contextual features (weather, calendar effects).

-- Subpart 2: Price Volatility and Dispatch Deviations --

✓ Probabilistic price forecasting allows scenario-based dispatch planning under uncertainty.

✓ Ensemble learning and Bayesian models capture tail events and spikes — key for zones with high deviation risk.

-- Subpart 3: Infrastructure Reliability & Cyber-Physical Risk --

✓ ML methods for fault detection, outage localization, and early warning systems.

✓ Useful for scoring zones based on anomaly detection capability and SCADA robustness.

-- Cross-Cutting Methodological Value --

✓ Highlights the importance of explainable and scalable models — aligned with SGRI's transparency goal.

✓ Suggests model ensembles and uncertainty bands as resilience markers in operational forecasting.

-- SGRI Integration Ideas --

✓ Use forecasting reliability (e.g., prediction interval width or coverage) as an input to readiness scoring.

✓ Score zones based on their adoption of probabilistic modeling in load or price operations.

✓ Combine anomaly detection metrics with physical stress indicators for composite zone classification.

Recommendation:

Incorporate probabilistic ML metrics as part of your zone-level forecasting capability dimension. Use the reviewed models to support stress prediction and adaptive response design for Ontario’s electricity zones.

**SUMMARY: Robust Data Predictive Control Framework for Smart Multi-Microgrid Energy Dispatch Considering Electricity Market Uncertainty**

This paper presents a hybrid framework called RDPC-EMS (Robust Data Predictive Control - Energy Management System) for smart energy dispatch in cooperative multi-microgrid (MMG) systems under electricity market volatility. It combines:

1. \*\*Electricity Price Forecasting (EPF)\*\* using a machine learning algorithm:

- \*\*Outlier-Robust Extreme Learning Machine (OR-ELM)\*\*, outperforming SVR and ANN in forecasting accuracy.

- Uses real-world data from ISO New England and seasonal sampling to improve EPF.

2. \*\*Two-Layer Distributed Model Predictive Control (DMPC):\*\*

- \*\*First Layer (DSO level):\*\* Optimizes day-ahead scheduling using EPF and coordinates energy trading across microgrids.

- \*\*Second Layer (Local Controllers):\*\* Executes local dispatch (battery charge/discharge, DG use) based on DSO signals to maintain supply-demand balance.

3. \*\*Key Components Modeled:\*\*

- Energy storage systems (with charge/discharge efficiency and maintenance cost).

- Diesel generators (with fuel cost modeling and operation constraints).

- Renewable generation (PV from rooftop lab at Shanghai Jiao Tong University).

- Load demand types: critical and controllable.

- Retail price interaction with main grid.

4. \*\*Simulation Results:\*\*

- Case studies compared cooperative (energy-sharing) vs. non-cooperative operation.

- Cooperative mode reduced total operating costs by 15–16% for some microgrids.

- OR-ELM model showed superior forecasting (MAPE ~4.92%) and computation efficiency.

- Batteries and surplus power play a critical role in economic performance.

**RELEVANT POINTS FOR YOUR STUDY ON ZONAL ELECTRICITY STRESS AND SMART GRID READINESS:**

- The two-layer DMPC model supports \*\*resilient, cost-effective energy dispatch\*\* across zones (microgrids), useful for evaluating Smart Grid Readiness Index.

- The \*\*OR-ELM forecasting approach\*\* can be adapted for Ontario zones to anticipate price and dispatch uncertainty.

- Integration of \*\*critical vs. controllable loads\*\*, DERs, and inter-microgrid surplus exchange mirrors Ontario’s zone-level operational complexity.

- Provides a benchmark to \*\*quantify benefits of cooperative operation\*\* across electricity zones (e.g., using surplus in high-stress zones).

- The approach is data-driven and modular, supporting application to \*\*zonally decomposed Ontario grid simulation\*\*.

You could reference this as foundational for developing predictive dispatch control strategies that feed into your index-based investment prioritization framework.

**Summary: "Volatility of Power Grids Under Real-Time Pricing"**

Authors: Mardavij Roozbehani, Munther A. Dahleh, Sanjoy K. Mitter

Published in: IEEE Transactions on Power Systems, Nov. 2012

This study presents a theoretical and simulation-based framework for analyzing the impact of real-time pricing (RTP) in electricity markets. The central thesis is that RTP introduces a closed-loop feedback between supply, demand, and price, which can lead to increased system volatility and fragility without proper control mechanisms.

Key Concepts:

- RTP allows consumer demand to directly respond to wholesale market price signals.

- This feedback loop makes the system more sensitive to uncertainty and prediction errors, especially in demand behavior.

- Volatility is shown to depend heavily on the market's "Maximal Relative Price Elasticity" (MRPE)—i.e., the ratio of consumer to producer price elasticities.

- If MRPE > 1, the system becomes increasingly volatile and may destabilize.

- Lyapunov and contraction theory are used to derive stability conditions.

- Two models of consumer uncertainty are explored: multiplicative and additive perturbations.

- Simulations confirm that even small inaccuracies in demand prediction under high elasticity can cause significant price swings.

**Relevant Points for Your Study:**

- Use MRPE as a diagnostic metric for volatility in Ontario’s zonal electricity markets.

- The findings help analyze dispatch mismatches and price swings in Subpart 2 of your research.

- Highlights the risks of exposing consumers to RTP without buffering mechanisms (e.g., storage, demand caps).

- Supports the argument for differentiated pricing or zonal control mechanisms to mitigate volatility.

- Suggests that zones with higher renewable penetration or flexible demand (i.e., high elasticity) are more prone to instability.

- Advocates for real-time control laws and design considerations to stabilize feedback loops—this could feed into Smart Grid Readiness Index metrics.