TEMOA-Ontario: Community-Level Pathways to a Net-Zero Energy Transition

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***Abstract*—The TEMOA-Ontario model is developed to examine net-zero transition pathways for three representative communities: Toronto, Windsor, and Brighton. Emphasizing the comprehensive data collection and preparation process required to enable robust long-term energy planning. The model integrates multi-source datasets, including sector-specific energy demand, technology costs, and emissions intensities, harmonized into a consistent modeling framework spanning 2025 to 2050. The dataset construction incorporates end-use disaggregation, growth projections with electrification dynamics, and lifecycle emissions accounting, ensuring realistic representation of future energy transitions. Besides, system reliability is assessed with linearized loss of load probability formulation. This rigorous data foundation enables detailed scenario analysis, revealing how electrification and clean generation reshape local energy systems while maintaining reliability. The work demonstrates how systematic, community-level data integration supports the development of credible decarbonization pathways, providing a replicable methodology for planning net-zero transitions aligned with Canada's 2050 climate objectives.**

***Index Terms*— Data Collection, Emissions, Net-Zero, Optimization, Reliability.**

I. Introduction

Decarbonizing energy systems is a central pillar of global strategies to mitigate climate change. Canada, for example, has committed to achieving net-zero greenhouse gas (GHG) emissions by 2050, with the electricity sector expected to play a pivotal role in this transition [1]. Meeting this target requires a fundamental restructuring of how energy is produced, delivered, and consumed. Shifting from fossil fuels to low- or zero-emission sources, electrifying end-use sectors, and integrating new technologies across the system. While national and provincial policies set broad decarbonization goals, the specific pathways to achieve them vary significantly by region, reflecting differences in resource availability, infrastructure, urban form, and demand profiles [2].

Urban energy transitions present unique challenges and opportunities. Cities are major consumers of energy, usually responsible for more than 70% of global CO_2 emissions [3]. They offer scale economies for infrastructure deployment and are often early adopters of clean technologies. On the other hand, suburban and rural communities face distinct constraints, such as limited infrastructure density, different load characteristics, and reduced access to centralized energy systems [4]. Understanding how these factors shape energy system evolution is crucial for designing robust decarbonization strategies at the community level.

Several modeling studies have been proposed to explore long-term decarbonization pathways. For example, Integrated Assessment Models (IAMs) and national-scale energy-economy models such as Global Change Assessment Model (GCAM) [5], and The Integrated MARKAL-EFOM System Canada (TIMES-Canada) [6] have provided insights into technology deployment, sectoral transitions, and policy interactions. However, these tools often lack spatial and temporal granularity and may not capture community-level dynamics or sources operation constraints. Thus, bottom-up optimization models, such as Open-Source Energy Modeling System (OSeMOSYS) [7], Model for Energy Supply Strategy Alternatives and their General Environmental impacts (MESSAGE) [8], and Tools for Energy Model Optimization and Analysis (TEMOA) [9], offer greater flexibility to explore detailed sectoral transitions and localized policy interventions. In particular, TEMOA is a transparent, open-source linear optimization framework that supports reproducible and community-scale analyses. Its modular structure and publicly accessible code base have led to growing adoption in academic and policy contexts.

In [10] TEMOA-Europe is presented, a model designed for analyzing the European energy mix under scenarios aligned with the European Green Deal, Net-Zero Emissions by 2050, and the absence of Russian energy imports starting from 2030. Developed for Organization for Economic Cooperation and Development (OECD) Europe and calibrated against historical energy statistics up to 2020, the case study integrates technologies across demand and supply sectors (i.e., industry, transport, buildings, agriculture), applying detailed techno-economic characterization and employing a single-region spatial approach for simplified modeling and policy assessment. TEMOA is also applied to evaluate the potential trajectories of U.S. GHG emissions through 2040, assuming no

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new federal climate policies. This work provides insight into how existing trends and state-level actions might influence national emissions, highlighting regional and technological dynamics under policy uncertainty [11]. These applications highlight the transparency, accessibility, and reliability of TEMOA models.

While traditional planning approaches prioritize cost minimization and capacity adequacy, they often overlook how long-term system transitions impact the operational reliability of energy supply. To achieve net-zero by 2050, planners must therefore adopt methodologies that not only optimize economic efficiency and emissions reduction, but also evaluate system reliability, ensuring that the electricity grid can both accommodate higher demand and operate securely under the uncertainties of a decarbonized future. Different indices can be applied to assess the system's reliability, such as Loss of Load Expectation (LOLE), Expected Energy Not Supplied (EENS), Loss of Load Probability (LOLP), and Expected Unserved Energy (EUE) [12]. These indices capture different aspects of adequacy, ranging from the probability of supply shortfalls to the magnitude of unserved energy. In the context of evaluating emerging system configurations, studies such as [13] and [14] have applied LOLP to assess the reliability of capacity market models, highlighting its usefulness in balancing adequacy requirements with market-driven investment signals.

In this context, TEMOA is used to evaluate the energy transition pathways for three representative Ontario communities (i.e., Toronto, Windsor, and Brighton) aiming to deliver clean energy services by 2050. Toronto represents a dense urban center with high population and complexity. Windsor exemplifies a suburban-industrial region with mixed energy demand, and Brighton provides a rural context with a less diversified energy infrastructure. Each region is individually modeled and evaluated. The analysis explores how end-use sectors in these communities' transition away from GHG intense emission sources toward electrification and how supply portfolios must evolve to meet the resulting electricity demand while minimizing costs. Besides, the evolution of system reliability through the time horizon evaluated is assessed with a linearized LOLP formulation.

The paper is organized as follows. Section II presents the TEMOA framework. Section III introduces the linearized LOLP formulation. Section IV describes the input data for illustrative Ontario case studies, which are evaluated in Section V. Section VI concludes the study.

II. TEMOA Framework

TEMOA is a technology-explicit energy economy optimization model designed to support robust, transparent energy system analysis. Its primary objective is to minimize the total system cost of energy supply while ensuring that specified end-use energy demands are met across a defined time horizon [9]. TEMOA is built for modern computational environments, implemented using Python [15], and Pyomo [16]. It requires users to explicitly define the energy system using a structured, algebraic approach built on sets, parameters, and constraints. Sets categorize the essential elements of the system, such as commodities, and technologies. Parameters provide numeric details, covering, for example, technology capital and operating costs, lifetimes, discount rates, and emissions limits. Custom constraints allow the modeling of real-world policy, resource, and technical bounds. The model can be solved by using the appropriate Python environment and solver (e.g., GLPK, CBC, CPLEX, Gurobi). Upon solving, TEMOA delivers an optimized solution including technology capacities installed per future period, technology activities, total system costs, considering investment, operational, and fuel expenses computed in present value, and emissions produced in relation to established limits.

III. Reliability Assessment

LOLP is a widely used probabilistic index for assessing system adequacy. It measures the probability that available generation capacity will be insufficient to meet demand during a given time interval, typically defined on an hourly or daily basis. By quantifying the likelihood of supply interruptions under varying demand and generation conditions, LOLP provides planners with a concise measure of reliability risk in power system operation and expansion. Having a higher total generation capacity than the demand does not guarantee the reliability requirement is fulfilled [14].

Mathematically, LOLP can be assessed as a probability function. A linear approximation of this function is proposed in [17] and [18], as shown in (1). Where CAP is the installed capacity of the generator i, PD is the peak demand. Moreover, C_1, C_2, and C_3 are pre-computed constants that must be calculated near the evaluated system as they may vary with different jurisdictions. For Ontario neighbourhood, the constants are assumed $2 \cdot 10^{-4}$, $1.8 \cdot 10^{-8} \mathrm{MW}^{-1}$, and $2.4 \cdot 10^{-8} \mathrm{MW}^{-1}$ respectively [14]. It approximates reliability under typical adequacy conditions but simplifies nonlinear and operational effects. As a result, the reliability metrics are intended for comparative, long-term planning.

$$LOLP = C_1 - C_2 \cdot \sum_{i \in \Omega^G} CAP_i + C_3 \cdot PD \tag{1}$$

IV. Data Collection and Preparation

The TEMOA-Ontario model database was constructed by integrating residential, commercial, industrial, and transportation demands with supply, cost, and emissions data, while embedding explicit electrification trajectories consistent with federal net-zero policy. The calibration year was 2025, and projections were extended to 2050 using Canada Energy Regulator (CER) Net-Zero Scenario growth rates [19]. Following, the process is detailed by sector.

A. Residential Energy Demand

For Toronto and Windsor, baseline household energy use was obtained from Natural Resources Canada (NRCan's) Survey of Household Energy Use (SHEU) survey [20]. Average household natural gas (NG) consumption was 62.8 GJ/household in Toronto and 71.3 GJ/household in Windsor. Average electricity use was 30.0 GJ/household and 30.7 GJ/household, respectively. Household sizes were set at 2.4 (Toronto) and 2.3 (Windsor) persons per household. With populations of 3,026,000 (Toronto) and 229,660 (Windsor), this produced citywide totals of approximation presented in Table I. Brighton's residential demand was derived from

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Independent Electricity System Operator (IESO) hourly smart meter data for Forward Sortation Area (FSA) code K0K (population 115,850) [21]. Since the FSA may cover a larger population and include seasonal dwellings in this case, the dataset was scaled to Brighton's population (12,081) and then doubled to adjust for seasonal dwelling effects. The final baseline electricity demand for Brighton was 386,206 MWh (≈1.39 million GJ) in 2024. Brighton's natural gas demand was set to zero, considering the absence of piped NG service. All the residential demand information is summarised in Table I.

TABLE I. RESIDENTIAL ENERGY DEMAND BY AREA

Area	NG demand 2025	Electricity demand 2025
Toronto	79.2 PJ	37.8 PJ
Windsor	7.1 PJ	3.1 PJ
Brighton	0 GJ	1.4 PJ

B. Commercial and Industrial Sectors Energy Demand

Toronto's sectoral splits were taken from its 2022 Sector-Based Emissions Inventory [22]: 21.5% residential, 70% commercial, 8.5% industrial for electricity, and 57% residential, 32% commercial, 11% industrial for natural gas. Windsor's allocation followed the Community Energy Plan [23], which reported 32.8% residential, 34.3% commercial, and 32.9% industrial shares for total energy demand. Subsequent disaggregation into gas and electricity was made using neighborhood-level gas/electricity ratios. In this case, City Centre is considered the commercial demand, and Walkersville the industrial. Then, equations (2) to (5) provide the electricity and gas splits for residential, commercial, and industrial activity for the suburban-industrial region.

$$Com.Electr.Cons. = 0.3818 \cdot Com.Ener.total \tag{2}$$
$$Com.NG\ Cons. = 0.6182 \cdot Com.Ener.total \tag{3}$$
$$Ind.Electr.Cons. = 0.3077 \cdot Ind.Ener.total \tag{4}$$
$$Ind.NG\ Cons. = 0.6923 \cdot Ind.Ener.total \tag{5}$$

Brighton's energy was obtained using Ontario's provincial averages (33% residential, 37% commercial, 29% industrial), with the simplifying assumption that all demand is electric due to the absence of NG pipelines. Table II organizes all the energy demand by sector.

TABLE II. COMMERCIAL AND INDUSTRIAL ENERGY DEMAND BY AREA

Area	NG demand 2025		Electricity demand 2025	
	Commer.	Indus.	Commer.	Indus.
Toronto	44.5 PJ	15.3 PJ	123.1 PJ	14.9 PJ
Windsor	6.6 PJ	7.1 PJ	4.1 PJ	3.2 PJ
Brighton	0 PJ	0 PJ	1.6 PJ	1.2 PJ

C. Transportation Demand

Ontario refined petroleum balances from [24] were converted into per-capita consumption as presented in (6). Moreover, the energy conversion (ε^{Fuel}) applied for gasoline and diesel are, respectively, 34.66 GJ/m³ and 37.68 GJ/m³. Then, applying population scaling fuel consumption (ω_A) resulted in city-specific totals as shown in (7) that were introduced as 2025 baseline transport demands for each specific area (A). The transition process embedded in the CER scenario expected a gradual decline in combustion-based transport and a compensating rise in electricity use for electric vehicles (EVs). In TEMOA-Ontario, this was enforced via decreasing rate for gasoline and diesel vehicles, coupled with increasing rate for EV electricity demand.

$$PerCapita_{year}^{Fuel} = \left(\frac{NetProduction + Imports \\ -Exports - StockChange}{Population_{Ontario}} \right) \tag{6}$$

$$Consumption_{A,year}^{Fuel} = PerCapita_{year}^{Fuel} \cdot \omega_A \cdot Population_A \cdot \varepsilon^{Fuel} \tag{7}$$

D. End-Use Disaggregation

End-use allocations were derived from Statistics Canada's Comprehensive Energy Use Database [25]-[26]. In the residential sector, delivered energy was distributed as 64% for space heating, 17% for water heating, 14% for appliances, 3% for lighting, and 2% for cooling. The same methodology was applied to commercial demand. For Toronto, this breakdown translates into a residential space-heating load of roughly 50.7 million GJ in 2025, calculated from the baseline NG consumption. At the calibration year, space and water heating end uses were modeled as being primarily supplied by NG. However, consistent with the electrification trajectory, these demands progressively transition to electricity over the planning horizon.

E. Electricity Supply Capacities and Capacity Factors

The existing generation capacity for each city was estimated by scaling Ontario's transmission-connected capacities by technology in proportion to local electricity demand. A scaling factor (k_A) was defined for each area as the ratio of the city's required 2025 annual electricity demand (MWh) to Ontario's total annual generation (MWh). Each provincial technology capacity was then multiplied by k_A to obtain the city-level allocation. Ontario's most recent year-end electricity output mix [27] was subsequently applied to apportion each city's 2025 requirement across technologies, using the shares of 50.9% nuclear, 24.1% hydro, 15.7% gas/oil, 8.5% wind, 0.5% solar, and 0.3% biofuel. This approach was adopted to establish a consistent and transparent baseline in the absence of detailed city-level generation data, while preserving Ontario's observed technology mix and IESO-reported capacity factors. Regarding the mix expansion, it is assumed that Toronto and Windsor could not build new hydro after 2025. Although, Brighton was allowed hydro expansion due to Lake Ontario's resource.

Besides, the capacity factor represents the ratio between a generator's average output over a given period and its installed nameplate capacity. This dimensionless metric ranges from 0 to 1 and reflects how intensively a unit is utilized relative to its maximum potential. To capture seasonal variations and operating patterns, monthly capacity factors were calculated for each technology. These were derived from IESO records of monthly generation by fuel type [28] in combination with Ontario's transmission-connected installed capacities [27]. This approach provides a representation of technology availability, ensuring that the modeled supply mix reproduces the observed performance characteristics of Ontario's power system.

F. Growth Projection and Eletrification

Sectoral demands were projected to 2050 using CER Net-Zero growth rates [19]. These projections incorporated energy

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transition dynamics: residential and commercial sectors gradually declining natural gas service volumes, replaced by electric heating and hot water systems. In transportation, fossil fuel use contracts over the evaluated period, while electricity demand rises in line with EV adoption trajectories. The industrial sector was also allowed to electrify, but at a slower pace, reflecting technological and economic constraints. This structure ensured that electricity demand grows, reflecting deep electrification. For example, Toronto total electricity demand expands from approximately 51 TWh in 2025 to 128 TWh in 2050, while Windsor increases from 2.95 TWh to 11.8 TWh.

G. Costs

Capital and operating costs for electricity generation technologies were sourced from the NREL 2024 Annual Technology Baseline (ATB) [29], which also presents most renewable cost forecasts used by the IESO. Reported values expressed in USD were converted to CAD using the average 2025 exchange rate. For wind and solar, costs were increased by 30% to reflect paired storage requirements due to intermittent generation [30]. End-use prices for electricity, NG, gasoline, and diesel were taken from [19]. These prices were applied uniformly to Toronto, Windsor, and Brighton, as provincial regulation ensures consistency in consumer pricing and taxation. Emission costs followed the Government of Canada's Minimum National Carbon Pollution Price Schedule (2023–2030) [31], starting at \$65 CAD/tCO_2e in 2023 and increasing by \$15 per year to \$170 CAD/tCO_2e in 2030. Beyond 2030, the same escalation rate was extrapolated linearly through 2050.

H. Emissions Factors

Service-level emission intensities for residential and commercial end uses, including space heating, water heating, appliances, lighting, and cooling, were derived from Statistics Canada's 2022 Comprehensive Energy Use Database [25]-[26]. Emission factors for gasoline and diesel were obtained from the same source under the transportation sector. The database reports both total energy use and associated GHG emissions, allowing fuel-specific emission intensities to be calculated as the ratio of emissions to energy consumption. For electricity generation, direct combustion emission factors for NG were taken from ECCC's National Inventory Report for stationary applications [32]. To account for upstream effects, lifecycle GHG intensities of electricity supply technologies were adopted from the IPCC Fifth Assessment Report [33]. In this work, the minimum reported values for each technology were applied, establishing a conservative baseline for lifecycle emissions.

V. RESULTS

The TEMOA-Ontario model results demonstrate how electrification and clean supply expansion reshape the energy portfolios between 2025 and 2050. Toronto exhibits the most pronounced transformation, with total electricity demand rising from 51 TWh in 2025 to 128 TWh in 2050. Gas service contracts steadily, reaching zero by 2050, while electricity becomes the exclusive energy carrier. Nuclear and wind dominate supply by mid-century, supplemented by stable hydro and incremental solar additions, as presented in Fig. 1.

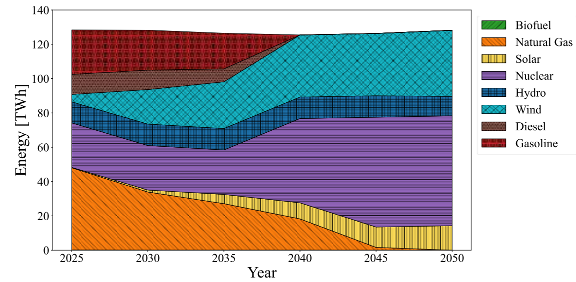

Figure 1. Energy mix over time for Toronto.

Emissions decline from the tens of millions of tCO_2e in 2025 to near zero by 2050, driven by the phase-out of natural gas, retirement of gasoline/diesel vehicles, and deployment of clean generation. Costs rise modestly through 2030, then accelerate as large nuclear and wind investments are added, before flattening post-2045 once the bulk of the portfolio is in place. Reliability remains robust, with low LOLP values increasing slightly after 2040 as peak demand grows without significant growth in supply installed capacity but staying within adequacy margins. It can be verified in Fig. 2.

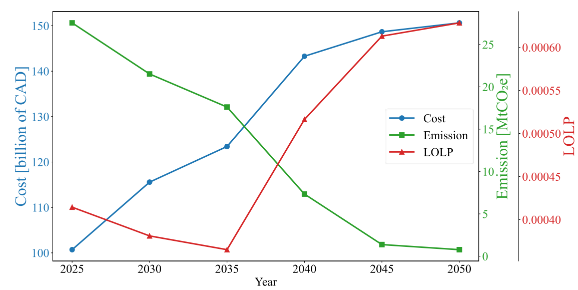

Figure 2. Total cost, emissions, and LOLP evolution for Toronto.

Windsor follows a similar electrification trajectory, though at smaller scale. Electricity demand grows from 2.95 TWh in 2025 to 11.8 TWh in 2050, with nuclear and wind again becoming the dominant resources. Gas service phases out by 2045, completing the transition earlier than Toronto. Emissions fall sharply and reach near-zero by 2045, consistent with the faster residential and commercial sectors switch. The cumulative cost profile mirrors Toronto's but remains lower in absolute terms due to Windsor's smaller system size. LOLP values remain low and stable, even improving slightly as dependable nuclear and wind additions track demand growth, demonstrating adequacy for a suburban-industrial system.

Brighton begins from a different baseline, with no piped natural gas and an electricity-dominated end-use profile in 2025 (i.e., 0.39 TWh rising to 0.53 TWh by 2050). Supply expansion is led by nuclear, hydro, and wind, with solar providing incremental growth. Emissions are small from the beginning, primarily tied to transport fuels. As EV adoption accelerates, gasoline and diesel use fall rapidly, producing near-zero emissions by 2035 and leaving only marginal upstream generator impacts thereafter. Costs remain far below Toronto and Windsor, reaching under CAD 1 billion by 2050, with the steepest increase during 2025–2035 when electrification accelerates. Reliability is stable, with LOLP values consistently around 2×10^{-4}, reflecting the adequacy of a relatively small but dependable supply mix.

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VI. Conclusion

TEMOA-Ontario model is proposed to evaluate energy transition pathways for three representative communities (i.e., Toronto, Windsor, and Brighton) under a net-zero emissions scenario. The results serve as illustrative case studies, showing how deep electrification of different sectors, coupled with large-scale nuclear and wind deployment, can eliminate nearly all direct emissions by 2050 while maintaining system adequacy. Toronto exhibits the greatest increase in demand and costs, Windsor demonstrates a faster phase-out of NG, and Brighton, starting from an electricity-dominant baseline, achieves the transition with minimal additional emissions. In all cases, LOLP values remained within acceptable limits, confirming that reliability can be preserved even as urban demand nearly triples. Beyond these specific cases, the study establishes a replicable framework, where the structured data collection process and TEMOA-Ontario model can be applied to other communities, supporting evidence-based planning for Canada's net-zero transition.

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