The Implications of Deep Decarbonization Pathways for Electricity Grids

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Introduction

Simultaneous technological changes including LED lighting, heat pumps, electric vehicles, battery storage, solar and wind technology, advanced telecommunications and information processing technologies are driving disruptive transformation in electricity consumption patterns. In parallel, the imperative to decarbonize the energy system is driving momentum around the world to electrify vehicles and building space and water heating.

Electrifying two of the most significant energy consuming activities in society has broad implications for the electricity grid. The way in which electrification is implemented and whether or not this process is accompanied by other actions will influence the nature of the impact on peak capacity of the electricity grid, the speed at which the grids can be decarbonized and the cost to society of the transformation.

Energy system modelers are increasingly being asked to address these and other questions, and the answers require that electricity demand and supply systems be modeled with greater temporal and spatial resolution than has been required of high-level energy system modeling in the past.

Background

SSG and whatIf? Technologies have developed decarbonization pathways for many communities in Canada, from the City of Toronto to the Town of Banff. The team has applied a bottom-up systems dynamics model, CityInSight, to evaluate these pathways.[1] The model tracks the evolution of the stocks of buildings, vehicles and energy consuming equipment and the consumption of energy and the production of GHG emissions on an annual basis in a zonal system. Energy supply is balanced against demand, and electricity from the provincial grid is treated as "imported" over the municipal boundary. Financial impacts are an output, as capital and operating cost intensities are applied to the stocks of equipment and energy consumed or emissions produced.

In each project we evaluate "actions" which are interventions that reduce GHG emissions, and these actions are iteratively adjusted in order to achieve GHG emissions reductions trajectories aligned with GHG targets or a carbon budget for a community.

[1] Background on CityInSight is available here: http://cityinsight.ssg.coop/ and is described in detail: Crockett, D., Herbert, Y., de Jager, M., Hoffman, M., Hoffman, R., Murphy, J., ... & Initiative, E. M. (2019). Modelling urban climate mitigation in Canadian municipalities.https://emi-ime.ca/wp-content/uploads/2019/12/P08_-Herbert_Spatially_Resolved_Modelling_of_Energy_and_Emissions.pdf

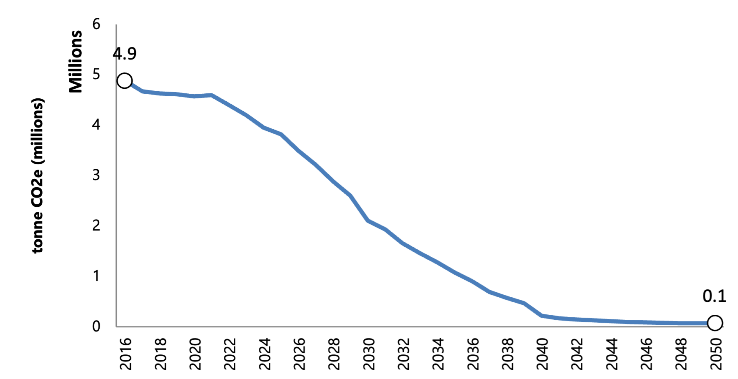

Figure 1: A decarbonization pathway for the City of Ottawa[2]

Our general approach is to order the actions according to a priority of 'Reduce, Improve, Switch'. Avoiding energy consumption is the top priority, followed by maximizing energy efficiency improvements, and finally by switching to low-carbon energy sources for the remaining demand. The strategy also prioritizes improvements to long-lasting infrastructure that can 'lock in' energy consumption patterns for many decades and takes advantage of opportunities to align proposed investments with the natural turnover of infrastructure and buildings.

The resulting pathways have a few characteristics which are generally common to all communities. Heating and transportation are electrified. Electrification of heating usually takes the form of the introduction of air source and ground source heat pumps, which increases the efficiency of heating by a factor of two to three or more. Similarly, the electrification of vehicles increases the efficiency of vehicle transportation by five to six times.[3] These efficiency gains mean that less electricity is required in total energy terms than is required to deliver the same services using natural gas and gasoline.

Building retrofits are also a core component in the pathways as they are assumed to reduce energy consumption in dwellings and buildings by at least 50%. Other measures which increase the efficiency of the system include increased transit, enhanced active transportation and compact land-use development.

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[2] SSG (2019). Energy Evolution: Technical Report. Retrieved from: https://app05.ottawa.ca/sirepub/cache/2/czkkkkr3fl42tpgbhsps5lcc/66271403252021110930961.PDF

[3] Oak Ridge National Laboratory for the U.S. Department of Energy and the U.S. Environmental Protection Agency. (n.d.). www.fueleconomy.gov. Retrieved from: https://www.fueleconomy.gov/feg/evtech.shtml

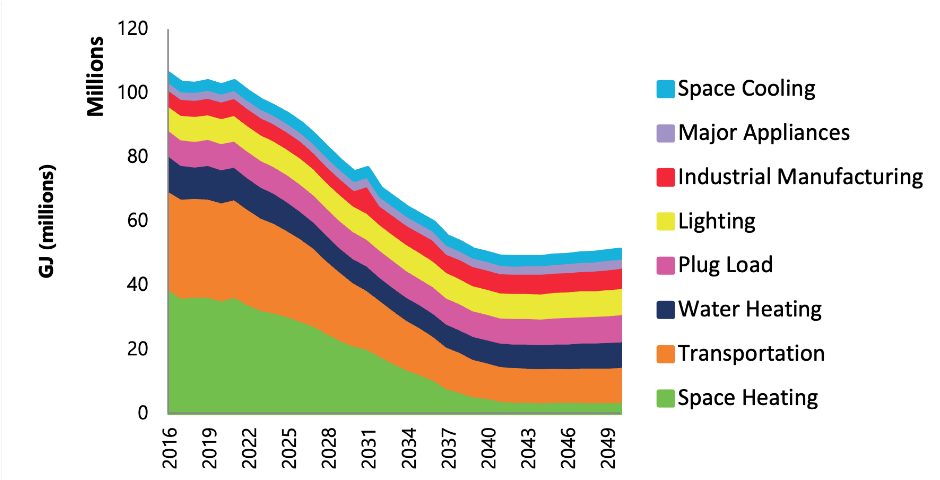

Figure 2: Efficiency gains in transportation and space heating for the City of Ottawa's Energy Evolution[4]

In the City of Ottawa, electricity consumption in 2016 is 28 million GJ and after heating and transportation is electrified by 2050, including a population increase from 1 million to 1.5 million, and a 70% increase in electricity consumption 48 million GJ.

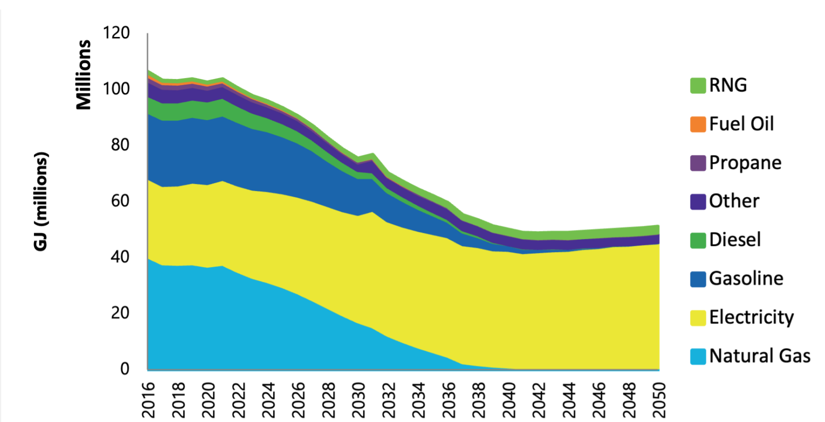

Figure 3: Electrification of transportation and heating for the City of Ottawa's Energy Evolution[5]

However, in a Business as Usual (BAU) scenario with limited penetration of electric vehicles and electric heating, total electricity consumption increases to 41 PJ in 2050, driven primarily by population growth. The BAU scenario includes 41 PJ of electricity, 41 PJ of natural gas and 24 PJ of gasoline, and the Energy Evolution scenario replaces all of that energy with 48 PJ of electricity, a reassuring finding for those responsible for running the grid. How is that possible? In the BAU scenario, 71.6 PJ is used for the energy service as intended whereas 42 PJ is lost in conversion primarily as heat. As energy has financial and ecological costs to generate and distribute, this 42 PJ is a societal burden. In the Energy

[4] Ibid

[5] Ibid

Evolution scenario, 42 PJ is used to provide the services the city requires, equal to what is lost in the BAU scenario, while 16 PJ is lost in conversion. The Energy Evolution scenario requires half as much energy in total and is 60% more efficient.

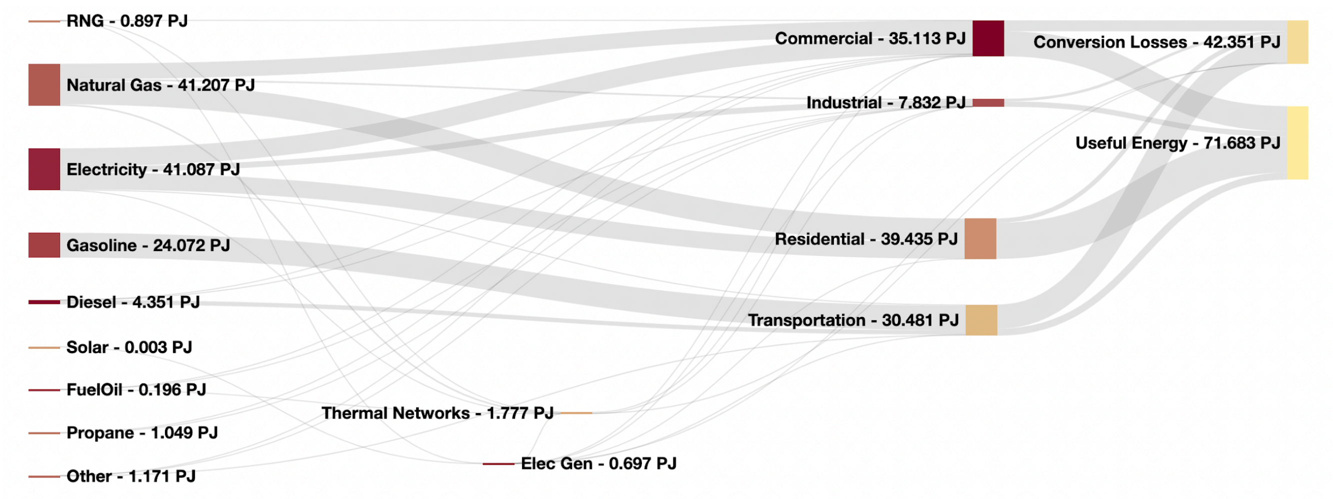

Figure 4: BAU scenario for the City of Ottawa's Energy Evolution, 2050[6]

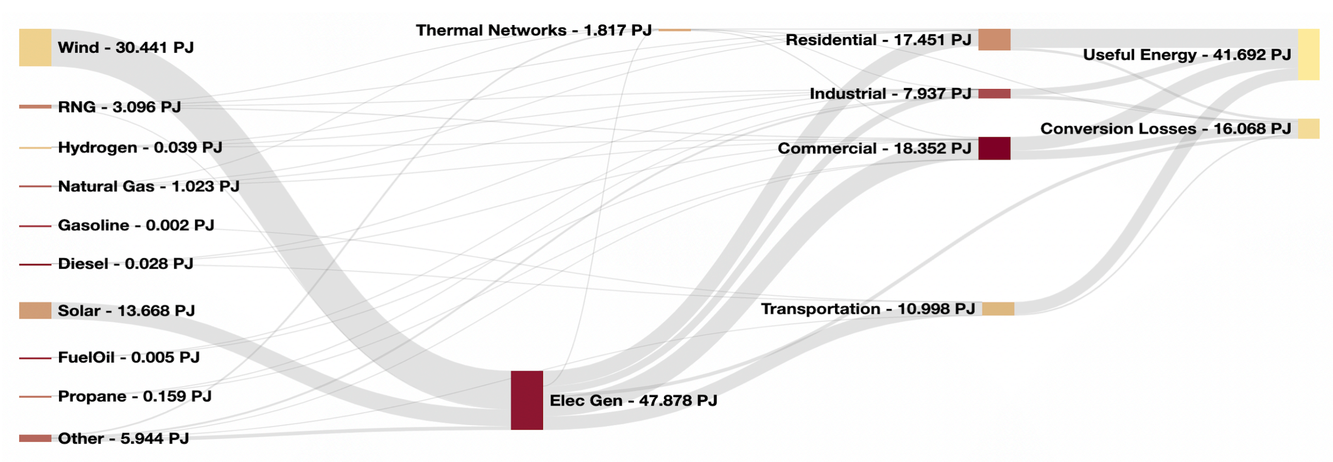

Figure 5: Energy Evolution scenario for the City of Ottawa, 2050[7]

NREL is in the midst of a major study to explore the impacts of electrification on all US sectors.[8] The analysis of demand used a similar modelling approach to CityInSight, in which analysts exogenously identify adoption rates for new technologies for three scenarios.[9] The scenario in which the most

[6] Ibid

[7] Ibid

[8] NREL (2019). Electrification Futures Study. Available here: https://www.nrel.gov/analysis/electrification-futures.html

[9] Mai, Trieu, Paige Jadun, Jeffrey Logan, Colin McMillan, Matteo Muratori, Daniel Steinberg, Laura Vimmerstedt, Ryan Jones, Benjamin Haley, and Brent Nelson. 2018. Electrification Futures Study:

electrification occurs is not as ambitious as the decarbonization scenarios which we generally implement; 84% of the light duty fleet is electrified by 2050, whereas we generally achieve 100% by 2050; and heat pumps account for 61% of residential space heating by 2050, whereas we generally achieve nearly 100%. NREL's analysis found that electricity consumption is 38% higher than the reference case by 2050, as a result of electrification of heating and transportation.

In addition to identifying the need for growth in generation of electricity, NREL's analysis points to other areas of transformation in the grid:

driven to a large degree by greater adoption of plug-in electric vehicles—electrification has the potential to significantly shift load shapes, particularly due to increased reliance on electric heat pumps for space and water heating needs. (p. xv)

The impact of the electrification pathway on the electricity grid is a question of debate and investigation,[10] and a question that is critical to address as the imperative to implement decarbonization policies becomes more imminent. In other words, our analysis of an annual time step is no longer sufficient to guide utilities and cities in the implementation of policies to achieve the transition to low carbon.

With NREL's more conservative electrification assumptions, the aggregate and coincident peak national hourly demand in 2050 is estimated to increase by 33% relative to the reference scenario. But this analysis does not consider building envelope improvements, an action that we argue is the keystone to ensuring the affordability of decarbonization pathways, delivering a wide range of co-benefits, reducing the cost of heat pumps and mitigating the impact on the electricity grid.

An Increasing, Shifting Peak

In partnership with Rocky Mountain Institute, SSG and whatIf Technologies analysed the energy and emissions profiles of a major building portfolio in Canada and using this analysis we were able to evaluate hourly results for a number of scenarios. Figure 6 illustrates total energy consumption before and after retrofit; natural gas is phased out and space heating is shifted to electricity, while overall building energy consumption declines by 39%.

Scenarios of Electric Technology Adoption and Power Consumption for the United States. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-71500. https://www.nrel.gov/docs/fy18osti/71500.pdf.

[10] For example, see this paper on the impact of the electrification of transportation: Muratori, M., & Mai, T. (2020). The shape of electrified transportation. *Environmental Research Letters*, *16*(1), 011003.

Three scenarios were evaluated for an 8760 analysis; in the baseline, the building is heated by natural gas; in the electrification only scenario, heat pumps are added; and in the scenario named Mountain Caribou, a package of retrofits is implemented including building envelopes and heat pumps. As expected, the electricity peak shifts from the summer to the winter, as the space heating load is electrified. The envelope retrofits have the effect of reducing the peaks.

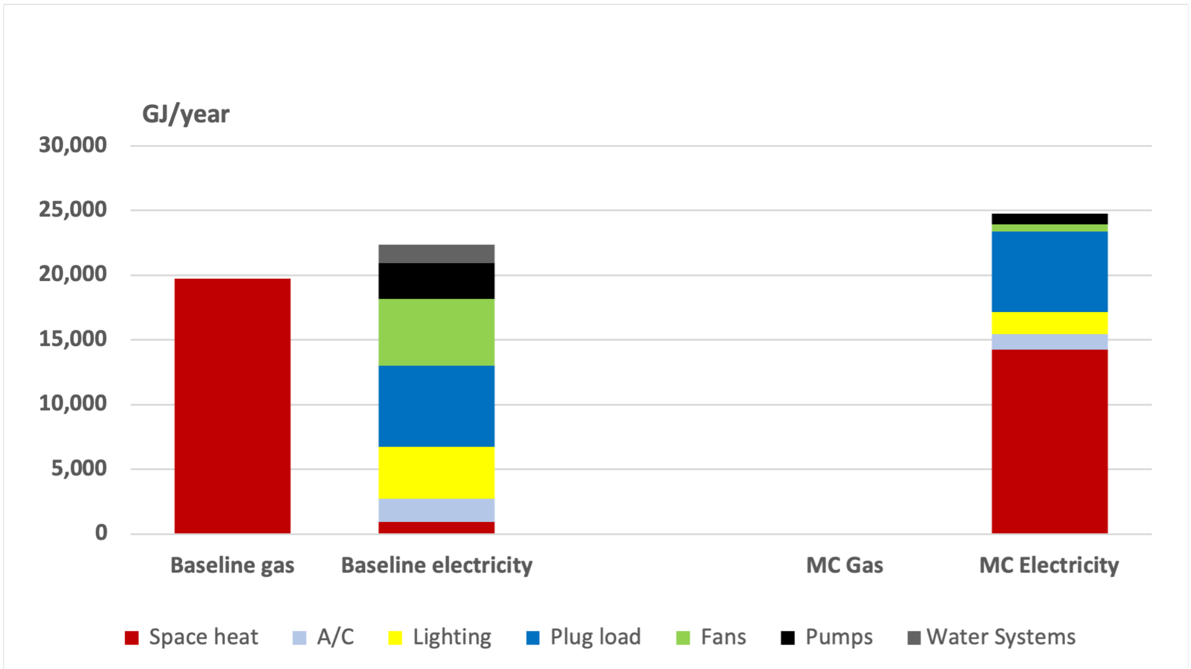

Figure 6: Office building, with multiple purposes (30,000 sqm)- Baseline vs. Mountain Caribou (MC) (Deep retrofit)

At the extreme, in the electrification only scenario, the winter peak jumps by 300%, but retrofits moderate the increase to 240% for this specific building; the results vary from building to building. Figure 8 and 9 zoom in to 24 hours in December and July to highlight the increase in peak as a result of electrification in the winter and the reduction in the summer, using the same scale on the vertical axis.

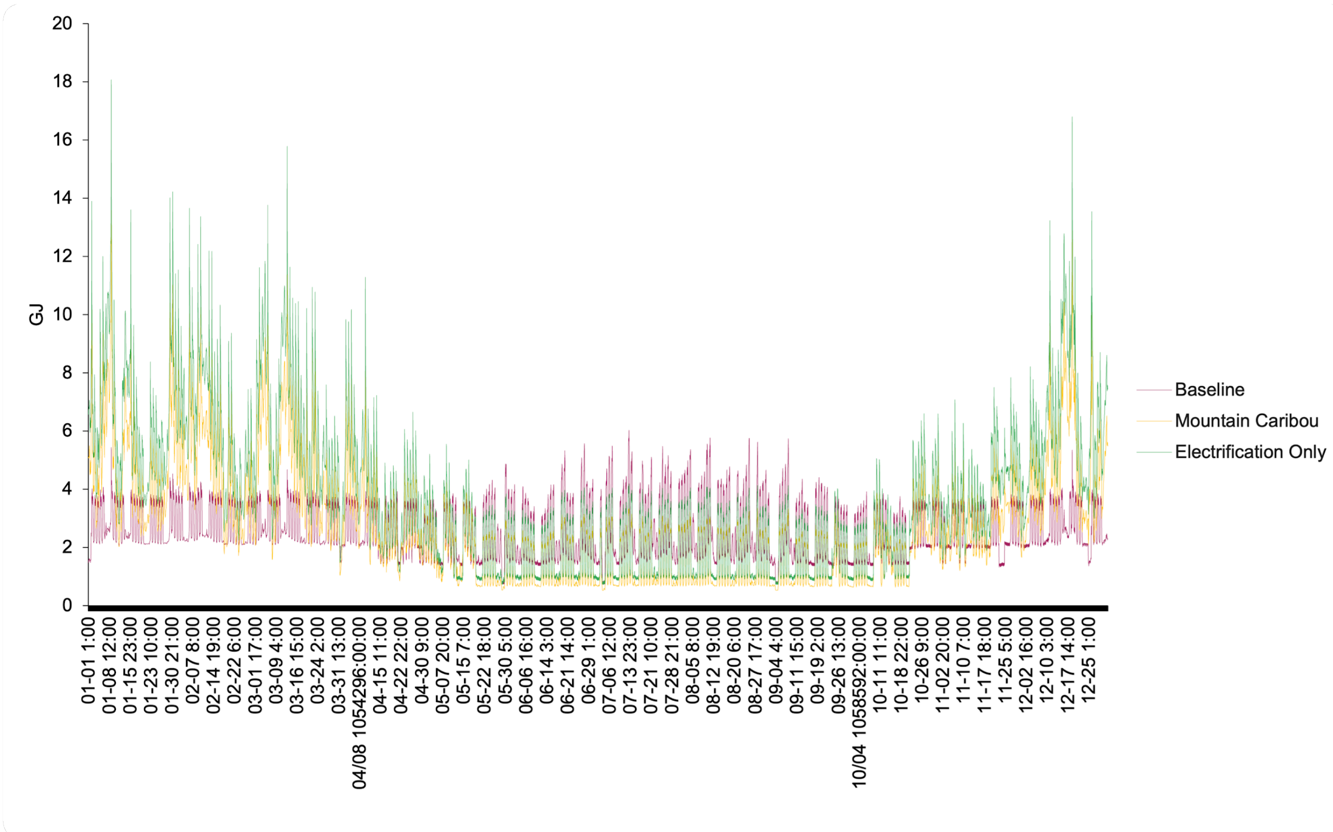

Figure 7: Three scenarios for a large natural gas-heated office building illustrating the impact of electrification of heating and retrofits on electricity demand for a year by hour.

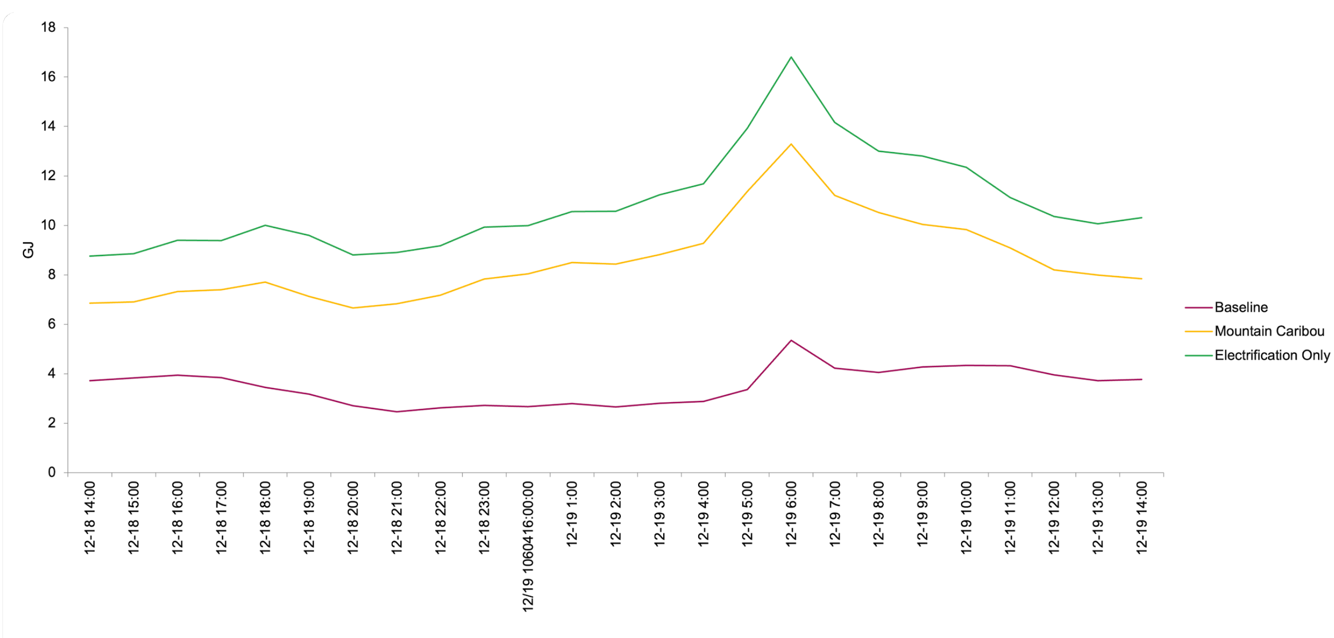

Figure 8: 24 hours in the winter for three scenarios for a large office building illustrating the impact of electrification of heating and retrofits on electricity demand

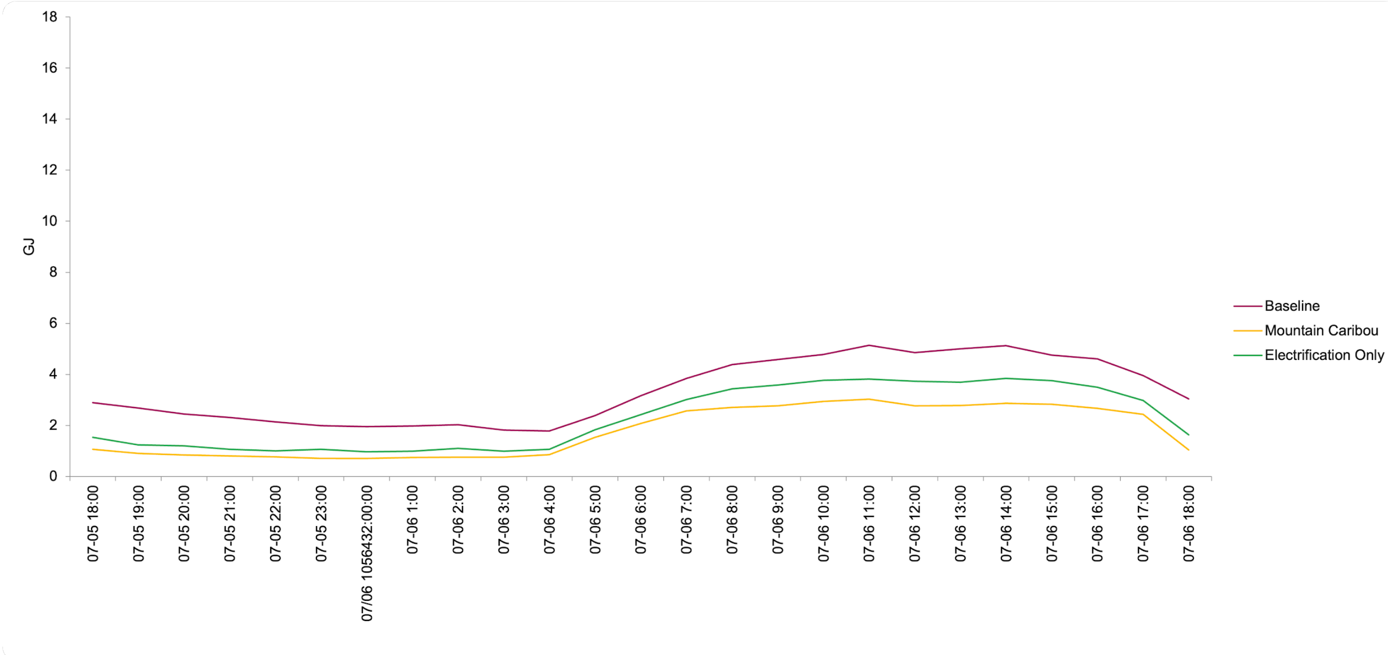

Figure 9: 24 hours in the summer for three scenarios for a large office building illustrating the impact of electrification of heating and retrofits on electricity demand

The Untapped Resource of Electrically Heating Buildings

A similar approach was applied to an electric resistance-heated building and the deployment of heat pumps reduces overall electricity consumption and peak demand as illustrated in Figure 9. In this case the winter peak declines precipitously, indicating that retrofits and heat pumps in buildings with electric resistance heating can provide efficiency gains which moderate the impact of electrification of heating and transportation. The ratio of buildings with electric resistance heating to buildings with natural gas heating will determine the increase or decrease of peaks, and this insight highlights the value of a system-wide analysis.

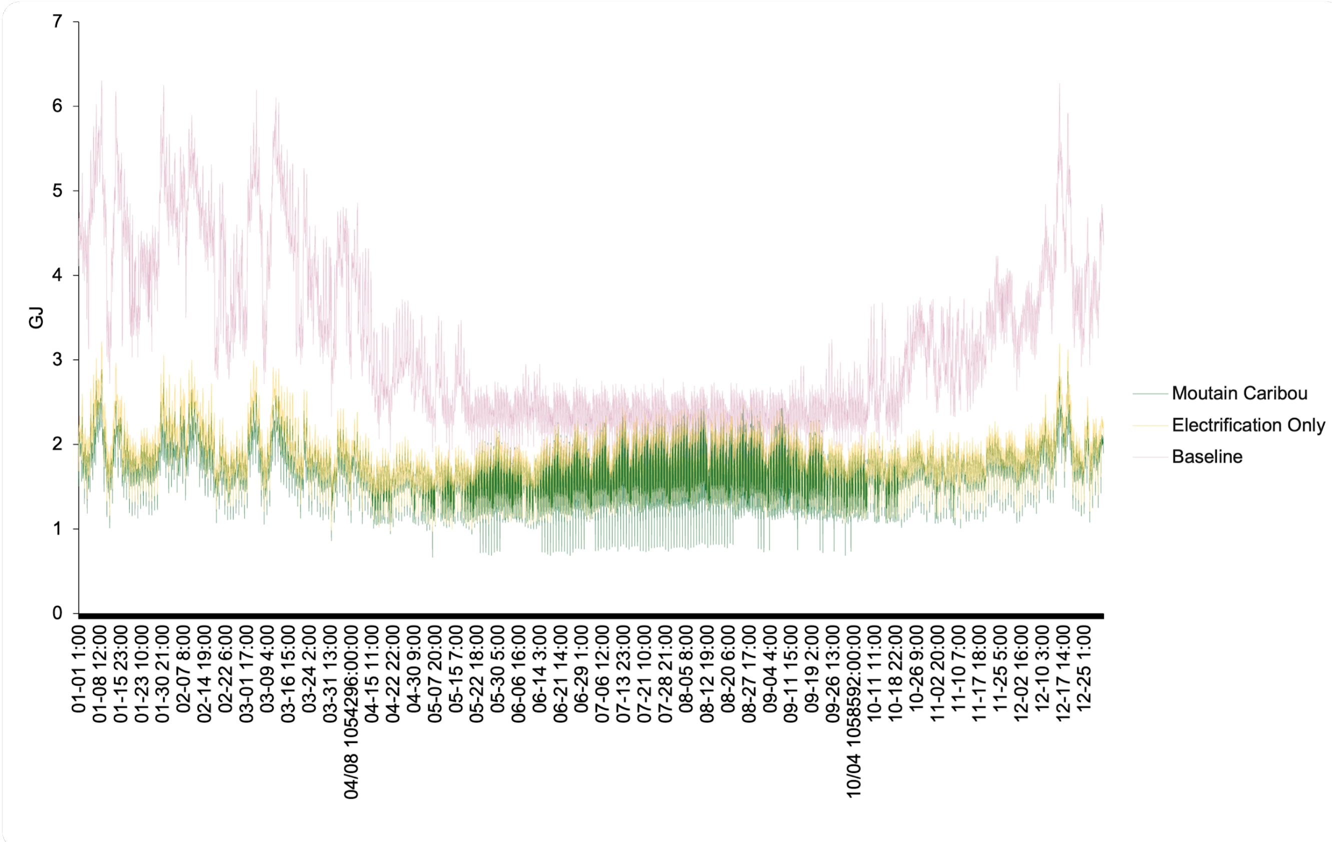

Figure 9: Three scenarios for a large electrically heated office building illustrating the impact of electrification of heating and retrofits on electricity demand for a year by hour

The Effect of Aggregation

The aggregate impact on load shape over multiple buildings has the effect of modulating the peaks for natural gas heated and electrically heated buildings, respectively. For naturally gas heated buildings, electricity demand currently peaks at 70 MW in the middle of the summer in the afternoon. After full electrification and retrofitting, these same buildings peak at 74 MW on a winter morning when the buildings are "ramping up" for the workday. It is the effect of improving the thermal envelope—the insulation and window upgrades—that keeps the peak from being much higher as a result of the electrification of heating.

The portion of the simulated portfolio that is electrically heated has a baseline peak that already occurs in the winter. However, while the shape of the load in the electrically heated buildings does not change very much as a result of the retrofits and heat pump transition, the peak drops by 26 percent, reflecting the impact of the heat pump efficiencies on electricity consumption for heating.

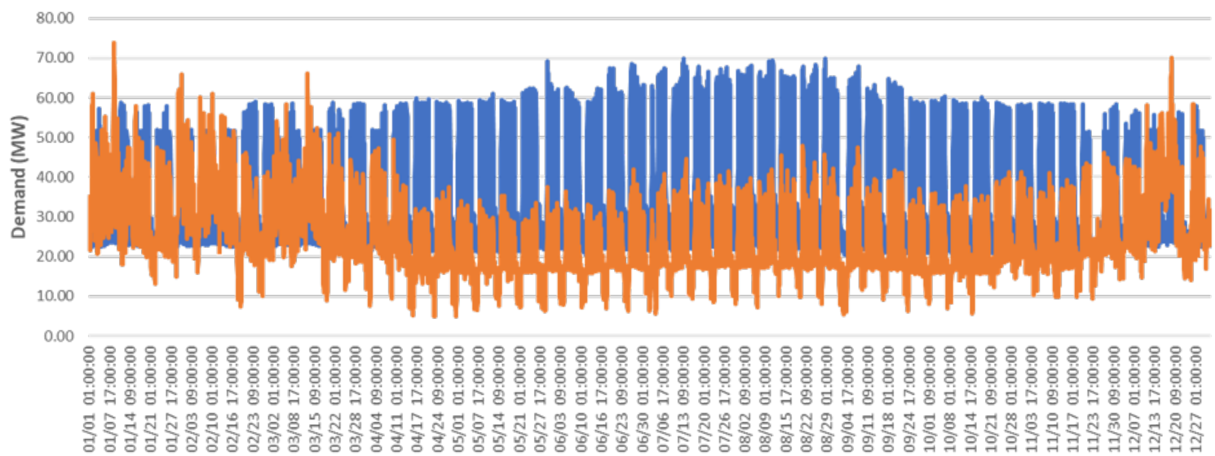

Figure 10. Daily peak demand of simulated natural gas heated buildings, baseline and post-retrofit and heat pump conversions

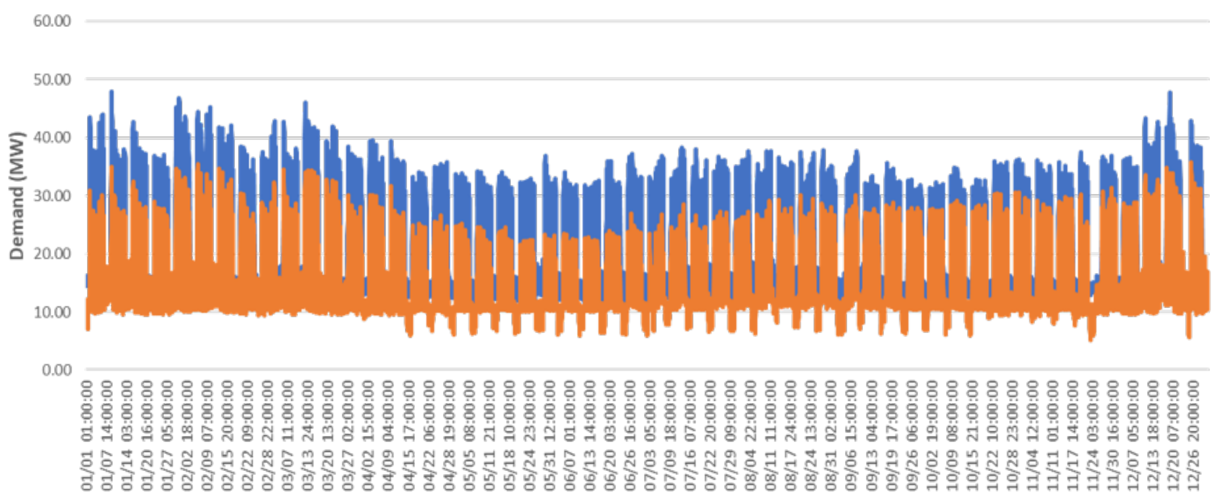

Figure 11. Daily peak demand of simulated electrically heated buildings, baseline and post-retrofit and heat pump conversions

The buildings included in these two portfolios have similar occupancy patterns and end-uses and including other building categories such as residential dwellings or different demand patterns (hospitals, supermarkets) will result in additional opportunities for balancing peaks to minimise the impact of electrification of heating on the grid. The variability of changing requirements for heating and cooling as a result of climate change is another factor which will impact summer and winter peaks, which we have not yet analysed. Using a projection of heating degree days and cooling degree days as a proxy for heating and cooling requirements, figure 12 indicates that the heating demand will decline, and the cooling demand will increase, indicating that the long-term weather patterns will moderate the winter peak.

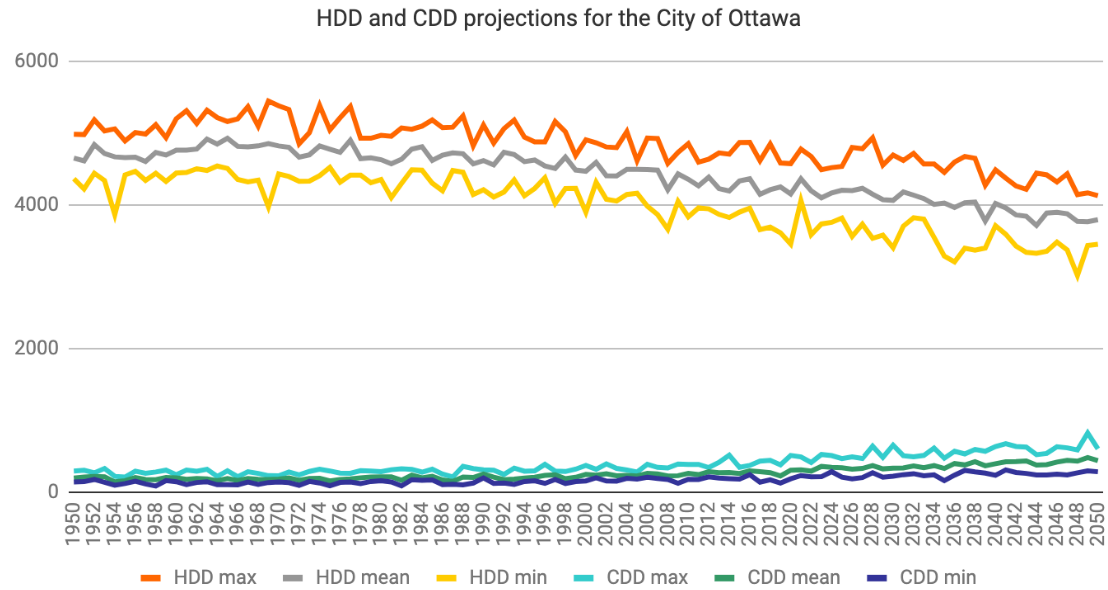

Figure 11. Annual heating degree days and cooling degree days for the City of Ottawa[11]

Adding Transportation to Mix

The electrification of transportation is the second major end use shift that occurs in the transition to low carbon. As with buildings, vehicle electrification results in a several-fold increase in efficiency at the point of end use, so much so that even in grids with significant fossil fuel generation still in their mix, the electrification of vehicles results in deep reductions in greenhouse gas emissions and air pollution.

Electric vehicles increase aggregate electricity use, but by 4-6 times less than the gasoline and diesel fuel consumption they displace. With today's technology, a typical personal electric vehicle driven 25,000 km per year, with an efficiency of 20 kwh/100 km (grid to wheels) has annual electricity consumption totaling 5,000 kWh. The battery holds 75-100 kWh, of which less than 20% is used in an average day's driving. Combustion vehicles are typically refueled every 400-500 km of driving, but as the network of home and community charging infrastructure builds out, electric vehicles will be connected to the grid most of the time they are not in use. The utilization rate of personal vehicles is typically no more than 5%, and even during rush hour most personal vehicles are parked, providing both flexibility with regard to when and how frequently the batteries are recharged.

The implication to energy system modeling of the portability of the EV load is that it requires both spatial and temporal representation. The EV load is inherently flexible regarding when the charging

[11] Projects for heating degree days and cooling degree days were sourced from the Climate Atlas: https://climateatlas.ca/

takes place -- they can be charged in off-peak periods, and do not necessarily need to be recharged every day. This makes them excellent candidates for demand management. While it is expected that personal vehicles will typically be charged at home, they can also be charged wherever chargers are available. To adequately respond to issues related to peak capacity implications of EV's and their effect on local distribution systems, energy system models will need to represent both the location and the timing of the EV charging load. This in turn will require that energy system models incorporate some of the data and algorithms used in transportation system modeling. The transportation component of the CityInSight energy system model is spatially resolved at the level of the urban traffic zone to support the analysis of the impact on trip making and transportation energy use of land use, zoning and active transportation policies. This will facilitate spatial representation of the EV load and charging network and combined with an 8760-hour representation of the charging load provides a powerful tool for assessing a wide range of questions related to the impacts of vehicle electrification on both the grid and the charging infrastructure.

If vehicle-to-load and vehicle-to-grid technology proves out, EV's will provide a significant amount of short term, portable battery storage that can be deployed when and where it is most valuable. The energy stored in an EV battery that could be made available (say, 25 kWh per day) is significant compared to peak period consumption of electricity by a typical household, and the level of energy stored in the EV fleet as a whole, once it is built out, will be significant relative to consumption at the community level. The representation of EV's in energy system models should therefore support analysis of their dispatch as electricity storage devices.

The Adaptation of CityInSight

A primary insight of this paper is that the addition of the capacity to undertake electricity demand analysis on an 8760 basis in CityInSight is conceptually straightforward. CityInSight is a powerful platform with which to evaluate future scenarios for the electricity grid as it represents all end-uses, sectors and fuel types and tracks the transitions of the energy system over time, as stocks of buildings and vehicles evolve over time and in space.

In order to represent the impacts on peak demand, hourly load shape profiles of EV charging and building energy end uses will need to be incorporated into the platform, with significant implications to required computer processing capacity. The model currently tracks multiple dimensions for each building, including size, end-uses, age of construction and location, and vehicles, including powertrain, age and location and as a result model run times are already an issue. A comparable analysis for the City of Los Angeles required the use of a supercomputer.[12] A possible data management strategy is to report in five-year increments as opposed to annually.

A question which was not evaluated in this paper is the electricity supply, in particular, the introduction of microgrids, solar PV and storage implemented at different scales. Conceptually, the model development path is similar, requiring the addition of hourly profiles and dispatch algorithms to integrate storage, demand management and intermittent supply in the system simulation.

From the perspective of an analyst, the addition of hourly profiles at the system level provides powerful resolution and potentially overwhelming complexity, which must be carefully managed and interpreted.[13] The hourly demand/supply analysis allows the identification and quantification of opportunities to move electricity consumption from times of the day when the renewable supply is maxed out to times of the day when it is in surplus, which is a critical dimension in decarbonising the grid.

Conclusions

City and community-scale analysis of energy and emissions pathways needs to incorporate consideration of the infrastructure that will enable the decarbonization of the energy system, in particular this means both spatial and temporal resolution of supply and demand dynamics in the electrical utility and distribution system.

Given that many decarbonization pathways focus on electrification of heating and transportation, strategies to manage or limit the disruption and/or transformation of the grid will reduce the financial and logistical burdens of addressing climate change.

As heating and transportation are the major energy consumers in many communities, minor adjustments or assumptions can have dramatic effects on the peak demand.

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[12] Cochran, Jaquelin, Paul Denholm, Meghan Mooney, Daniel Steinberg, Elaine Hale, Garvin Heath, Bryan Palmintier, Ben Sigrin, David Keyser, Devonie McCamey, Brady Cowiestoll, Kelsey Horowitz, Henry Horsey, Anthony Fontanini, Himanshu Jain, Matteo Muratori, Jennie Jorgenson, Matt Irish, George Ban-Weiss, Harvey Cutler, Vikram Ravi, and Scott Nicholson. 2021. "Executive Summary." In the Los Angeles 100% Renewable Energy Study, edited by Jaquelin Cochran and Paul Denholm. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-79444-ES. https://www.nrel.gov/docs/fy21osti/79444-ES.pdf.

[13] The NREL studies are examples of the complexity which must be considered.

The electrification of buildings shifts the peak demand from summer to winter, as major electrical load shifts from air conditioning to heating. The aggregate increase in the peak magnitude can be moderated by peak reductions from resistance-to-heat pump conversions and other efficiency gains resulting from a whole building retrofit.

Electric resistance-heating buildings are an untapped opportunity for peak demand management, and if retrofitted with heat pumps and enhanced envelopes, this building stock can generate "negawatts" which can be used to accommodate additional peaks from buildings converted from natural gas to electric heat pumps or electric vehicle charging.

Thermal envelope retrofits also generate tangible and intangible dividends by reducing the peak when a building is switched from natural gas to an electric heat pump. The tangible dividend is the avoided energy costs for the building owner or occupant, whereas the intangible dividend is the avoided cost for additional electricity generation and distribution capacity.

In the residential sector, the electrification of building space and water heating (via heat pumps) will likely result in decreases or only modest increases in aggregate electricity consumption, for most Canadian provinces, due to the market share of electric resistance heating.

The charging behaviour of EV owners or stewards can vary widely according to incentives and usage profiles. If vehicle-to-grid technology proves out, EV's will provide very significant storage capacity at the household level. As portable storage devices, EVs will also make possible the transfer of electricity in and out of neighbourhoods, with implications to distribution systems.

Limiting and managing demand facilitates the decarbonization of generation, and the addition of hourly profiles to an integrated energy systems model will continue to unlock new insights and explore trade-offs. For example, is retrofitting the electric resistance-heated building stock more expedient than adding additional wind, solar and battery capacity to the grid? How can vehicle-to-grid technology be used to manage solar and wind intermittency? Where are the necessary investments in transformers to accommodate EV charging and electrification of building heating?

Efficiency, electrification and decarbonization are interconnected and interdependent and realizing their full potential will require an integrated, systems approach to both policies and business strategies.