The Canadian Open Energy Model (CANOE)

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Davey Elder

Buildings
+workflow

Rashid Zetter

Transport

CANOE

Purpose

To envision the optimal roles and mix of chemical fuels across Canada while accounting for interactions across sectors and fuel production pathways

Gaps	Objectives
Existing models are mostly single-sector and/or proprietary	Build a transparent, accessible, multi-sectoral energy system model (ESM)
Opportunity for further integration of industrial ecology tools	Advance integration of life cycle (LCA), material flow and mid-transition constraints
Chemical fuels under-represented in Canadian ESMs	Emphasize assessment of chemical fuels in CANOE (industry, transportation)

CANOE

CANOE is a long-term planning model built on the TEMOA Platform

Type of model

- Energy systems optimisation model
- Capacity expansion
- Built on established Temoa framework

Spatial resolution

- National-provincial (one region per province)

Temporal resolution

- 5-year periods, 2025 → 2050
- Representative days with hourly resolution

Technological resolution

- Major existing and emerging technologies

Supply sectors

- Chemical fuels (liquid, gaseous fuels)
- Electricity

Demand sectors

- Industry
- Transportation
- Buildings

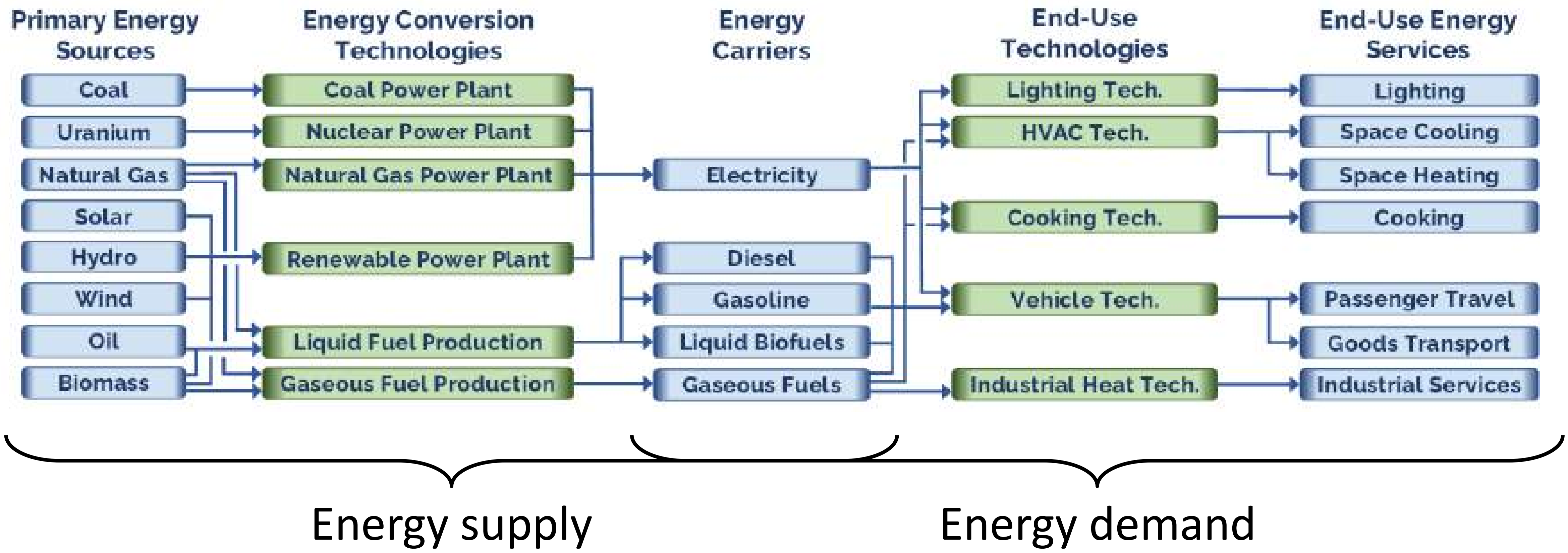
(Also carbon removal, e.g. direct air capture)

Outputs

- Optimised Capacities & Utilizations
- Minimized total system costs
- Emissions
- Other planned metrics (e.g., material use)

Systems representation – CANOE

(demonstrative subset of systems)



TEMOA overview

- Open-access, python-based optimization framework; transparent and easy to use
- Diverse and flexible functionality; designed for multi-sectoral applications
- Existing instances for US Open Energy Outlook, ACES (Atlantic Canada), LENZ (Toronto)

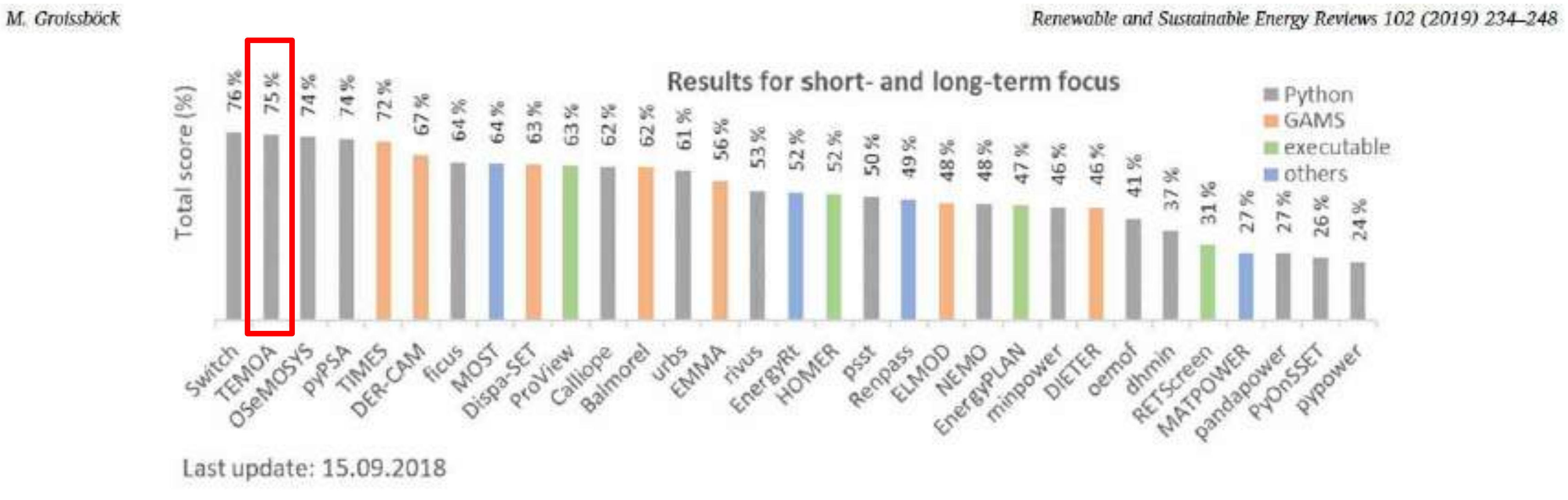
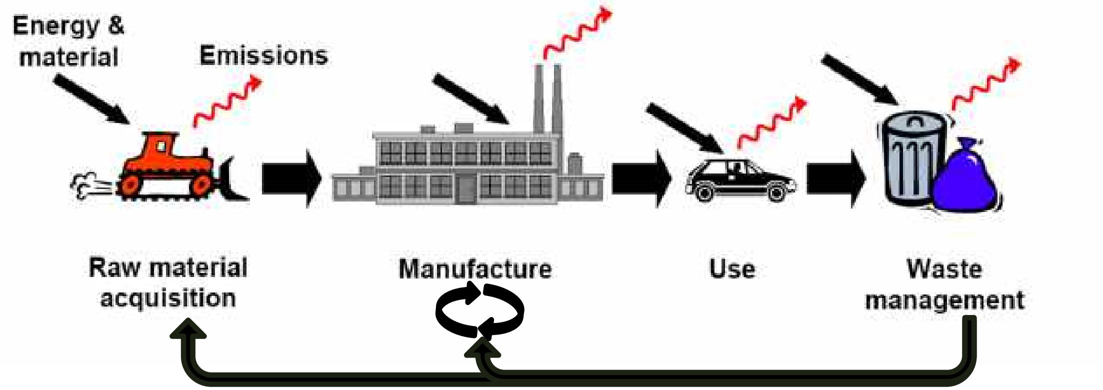
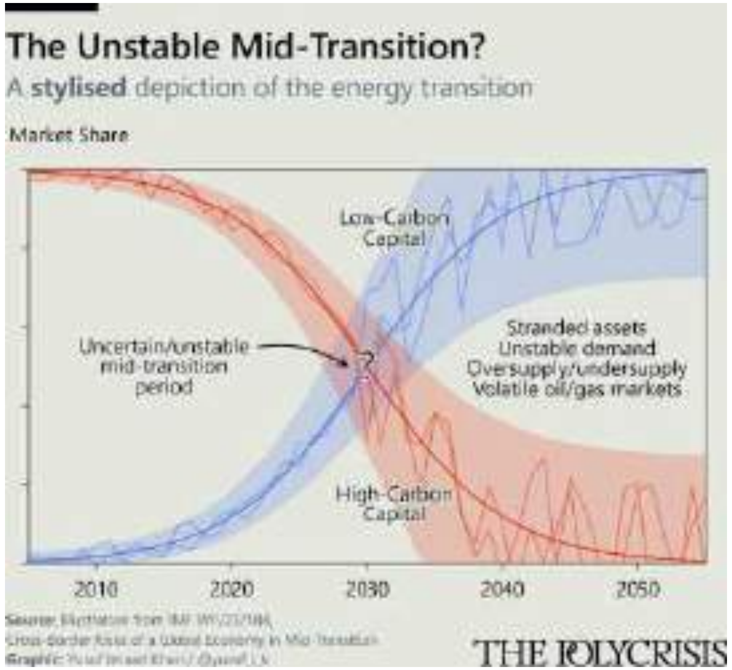


Fig. 1. Evaluation results with combined short- and long-term focus.

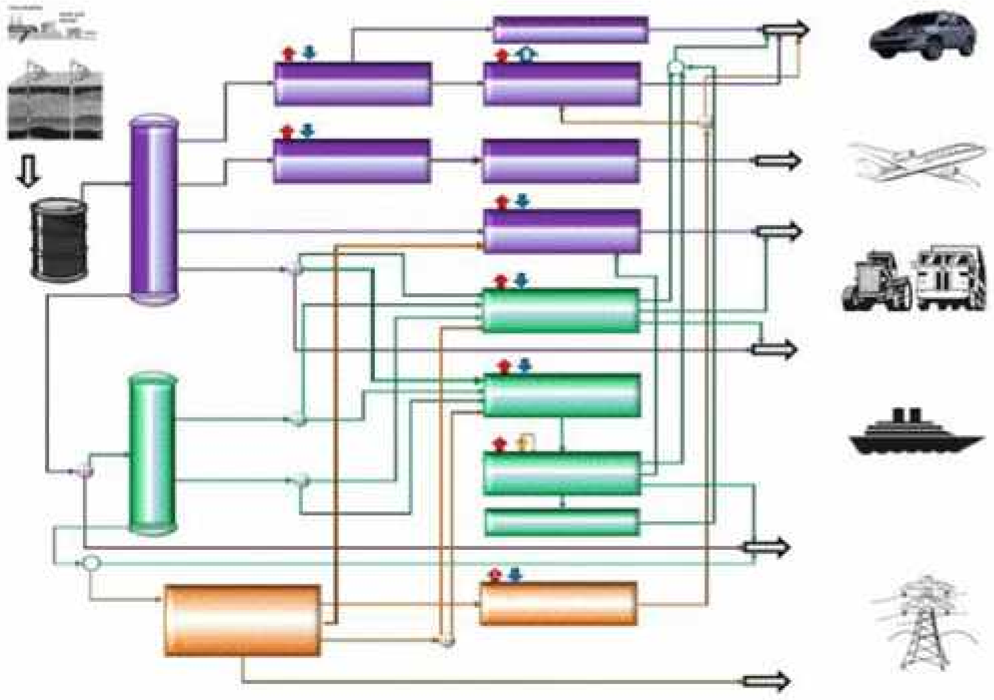
Planned contributions from adjacent research

Life cycle assessment and Material flow analysis





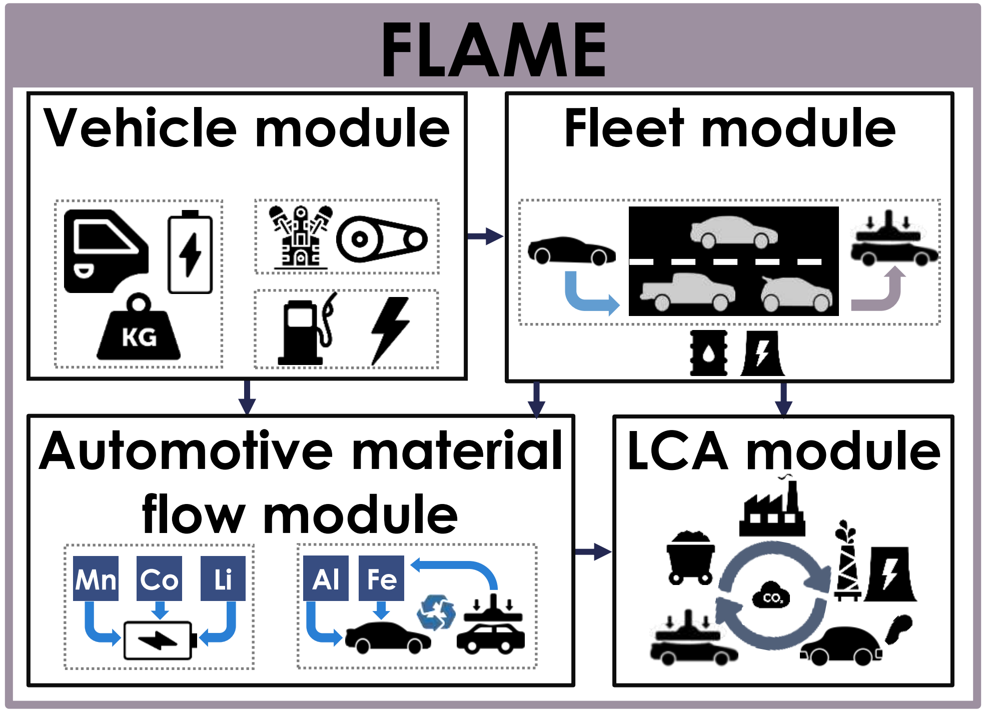
Improved representation of refineries

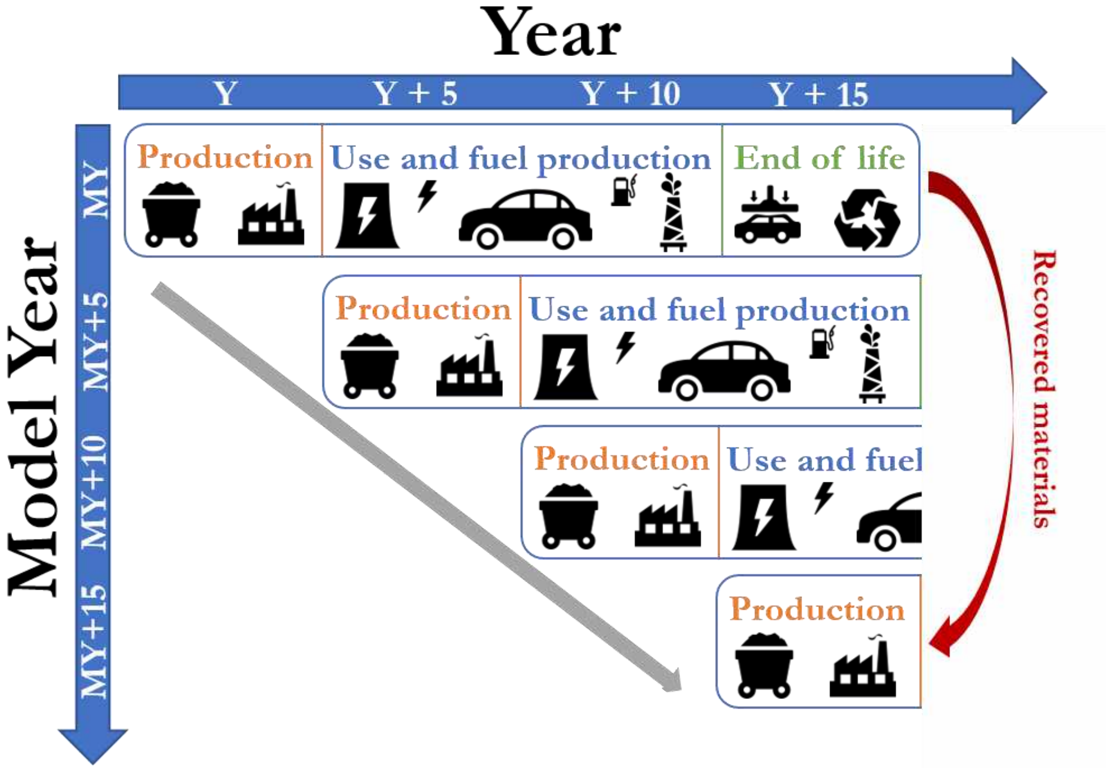


Abella and Bergerson 2012; Prelim model (updated 2022)

Side note: we've been building vehicle fleet LCA models for a while

The Fleet Life Cycle Assessment and Material Flow Estimation (FLAME) model





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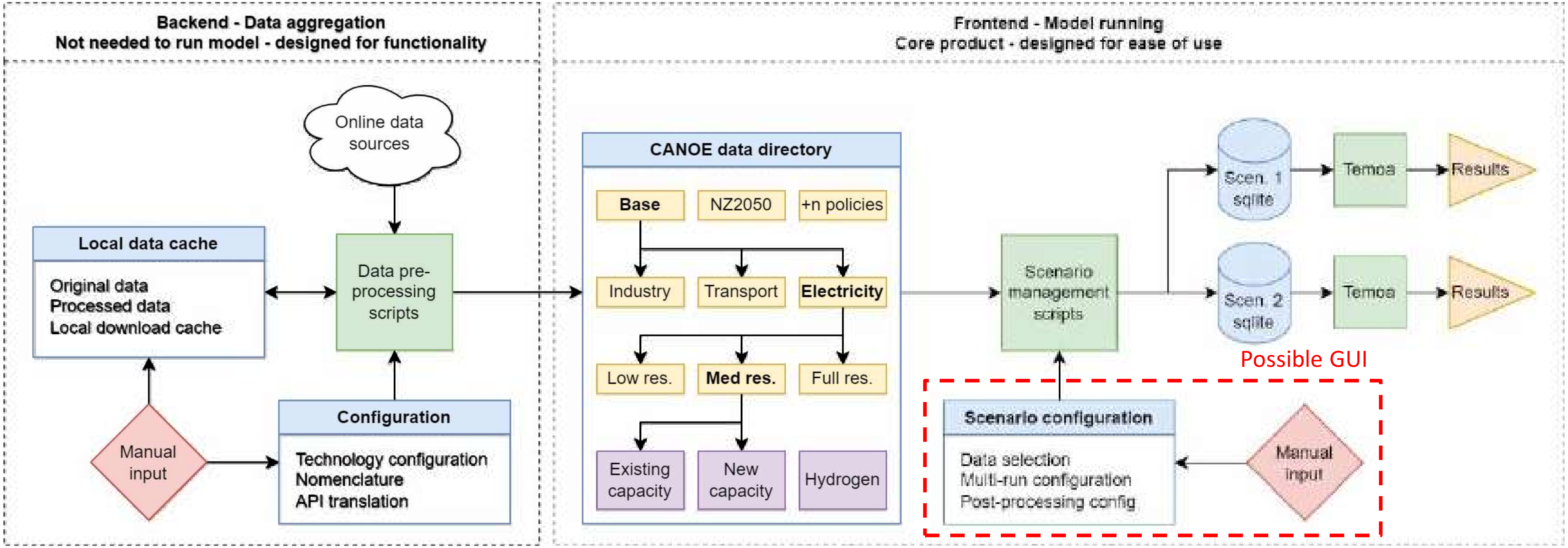
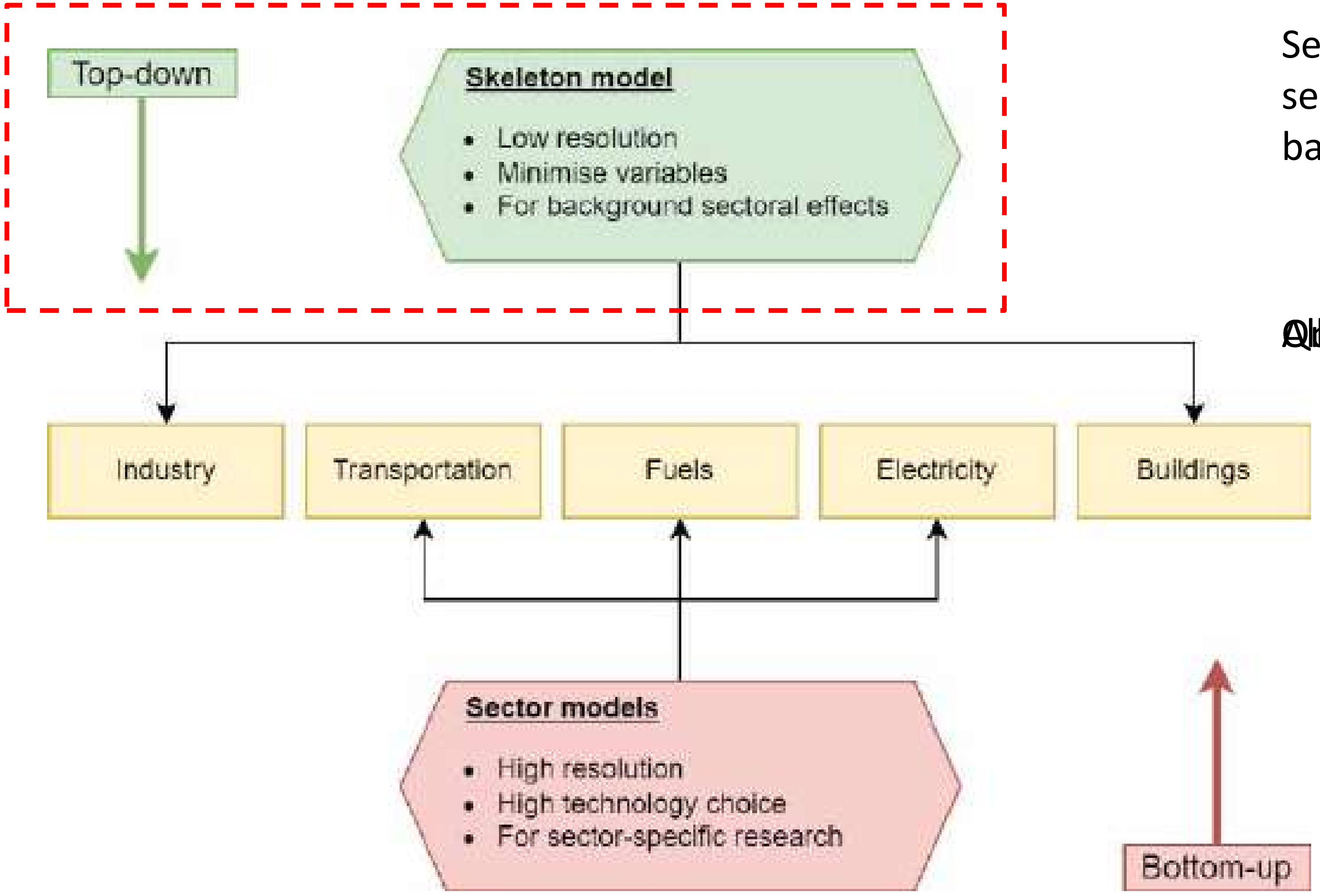
Back to the core CANOE model: Workflow



Model construction

Hybrid top-down, bottom-up approach



Select resolution per sector and per province based on planned analysis

Skeleton model

Top-down development

1st Generation

- Aggregation of technologies
- Aids in optimizing implementation going forward

2nd Generation

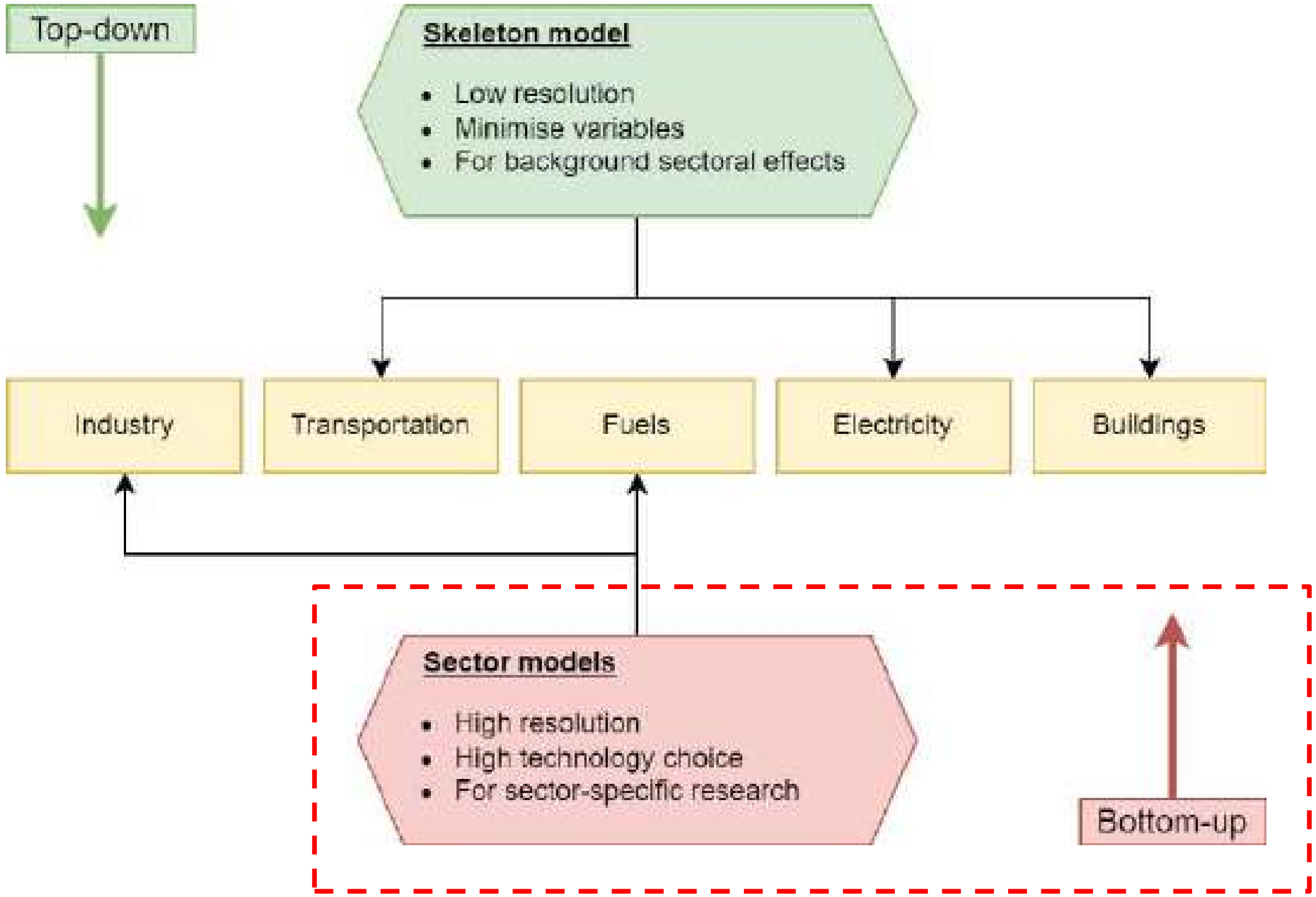
- Disaggregation of technologies
- Improve resolution of focus sectors
- Customizable degree of resolution for computational tractability

nth Generation

- All sectors highest resolution
- Insights from adjacent communities
- The final model to be solved, and most computationally demanding
- Perpetual (?) updates

Model construction

Hybrid top-down, bottom-up approach



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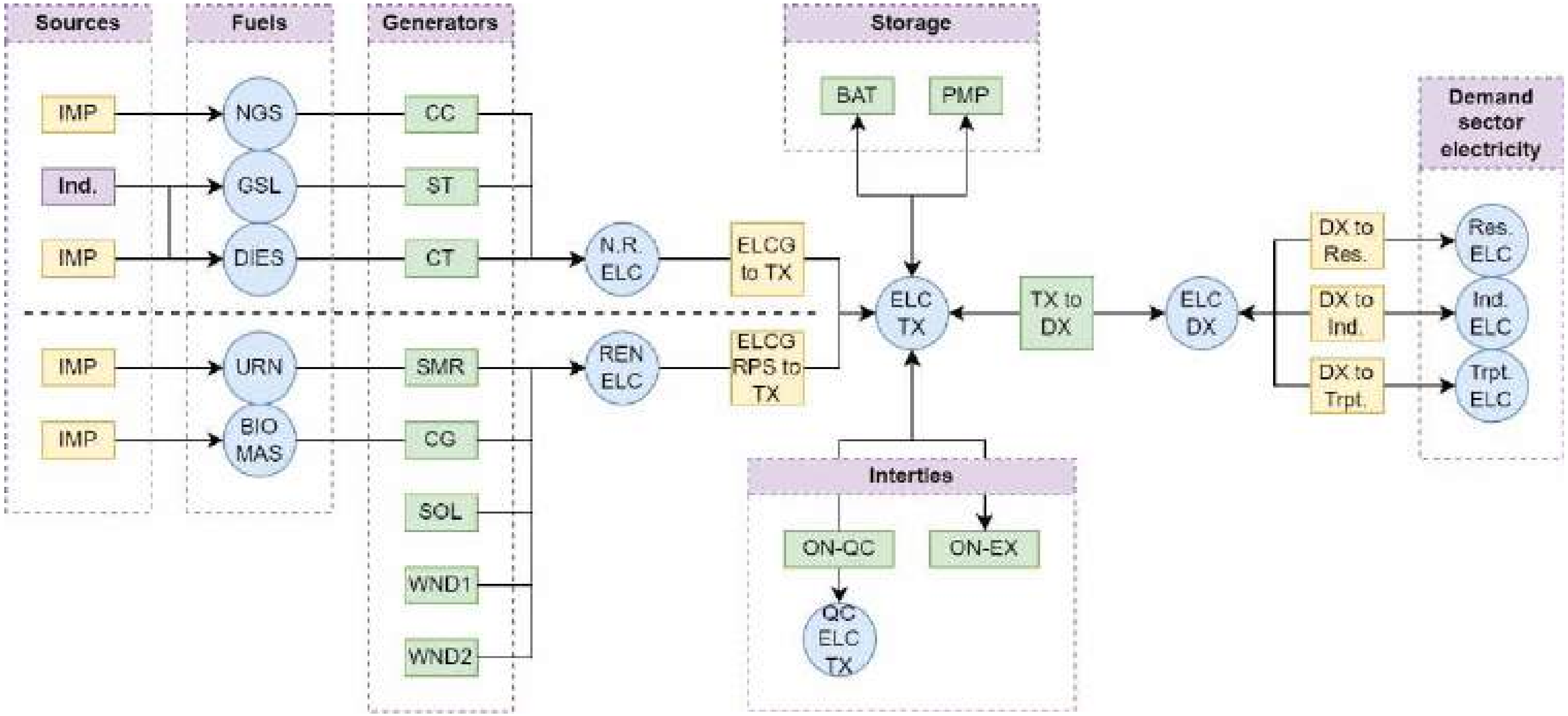
**Data from CODERS wherever possible*

Electricity

*Simplified structure**



Residential buildings

Simplified

Fuels
Electricity
Natural gas
Heating oil
Propane
Wood

CO2e

>

Technology choice
Fuel choice
High vs. typical efficiency

>

End use demands (hourly)	
Space heating	
Space cooling	
Water heating	
Lighting	
Appliances	Clothes dryers
	Clothes washers
	Cooking ranges
	Dish washers
	Freezers
	Refrigerators
	Other electrical appliances

Commercial buildings

Simplified

CO2e

Fuels
Electricity
Natural gas
Heating oil

>

Technology choice
Fuel choice
Heat pumps vs. separate techs

>

End use demands (hourly
Space heating
Space cooling
Other

Data sources - Residential

Similar for Commercial

Data	Technologies	Resolution	Source
Existing capacities	Existing stock	32 technologies, provincial	NRCan Comprehensive Energy Use Database
Efficiencies			
Capacity factors			
Demands		Annual, provincial	
Costs	New stock	57 technologies, census division	AEO (NEMS) input data
Lifetimes			
Efficiencies			
Demands	All	Hourly, US state	NREL ResStock 2018 + temperature mapping to Canada

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Buildings major challenges

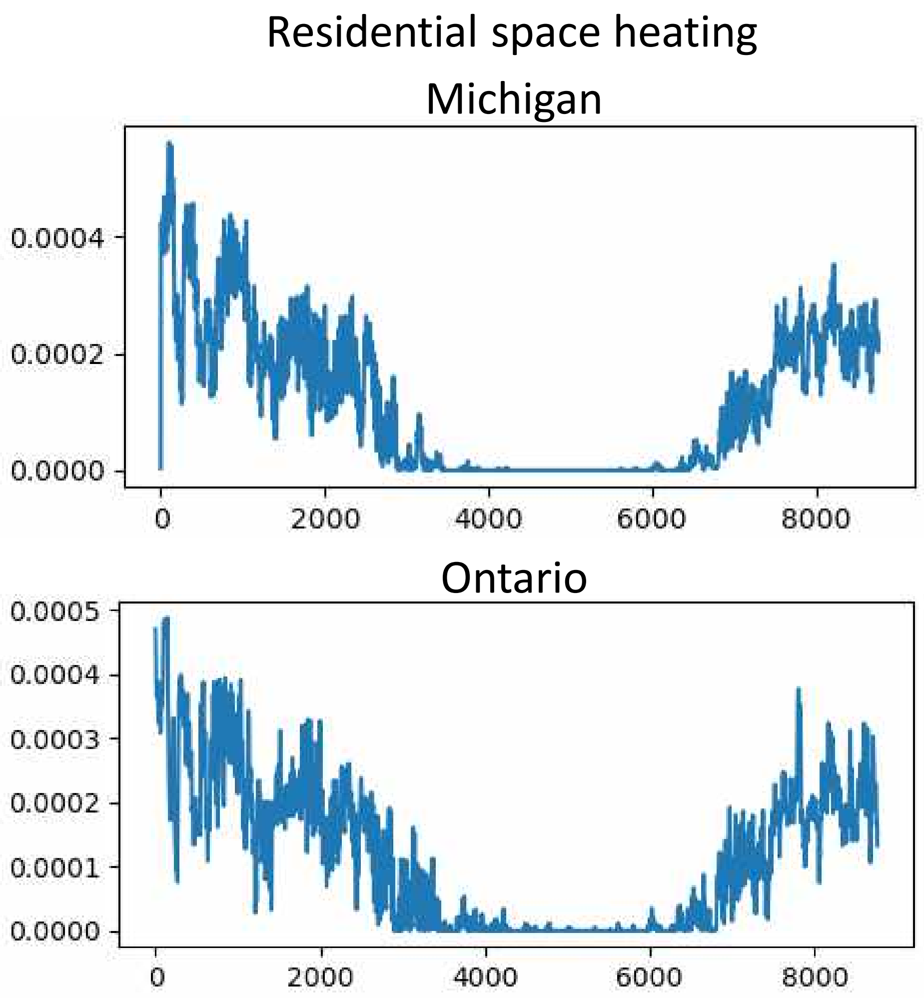
- Hourly demand profiles
- Annual capacity factors

Hourly demand profiles for buildings

Don’t have hourly end use demand profiles for buildings in Canada.

Solution:

1. Hourly demand per archetype from analog US states in NREL Res/ComStock
2. Index US building archetypes to Canada building stock
3. Map to Canada by population-weighted hourly temperature (Renewables Ninja),
   – i.e., using mean of any hours matching relative humidity and temperature (± 1°C)
4. Normalise



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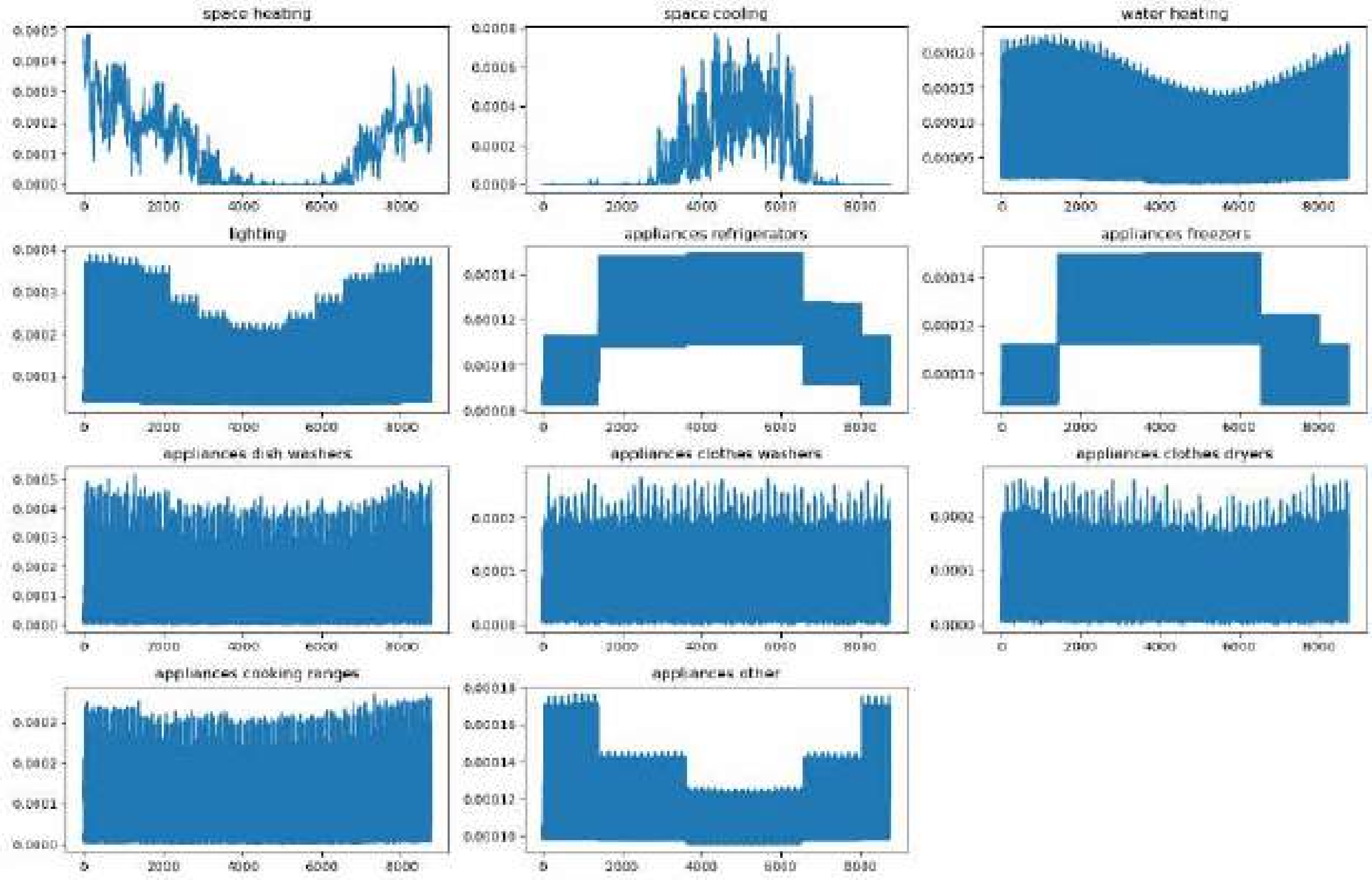
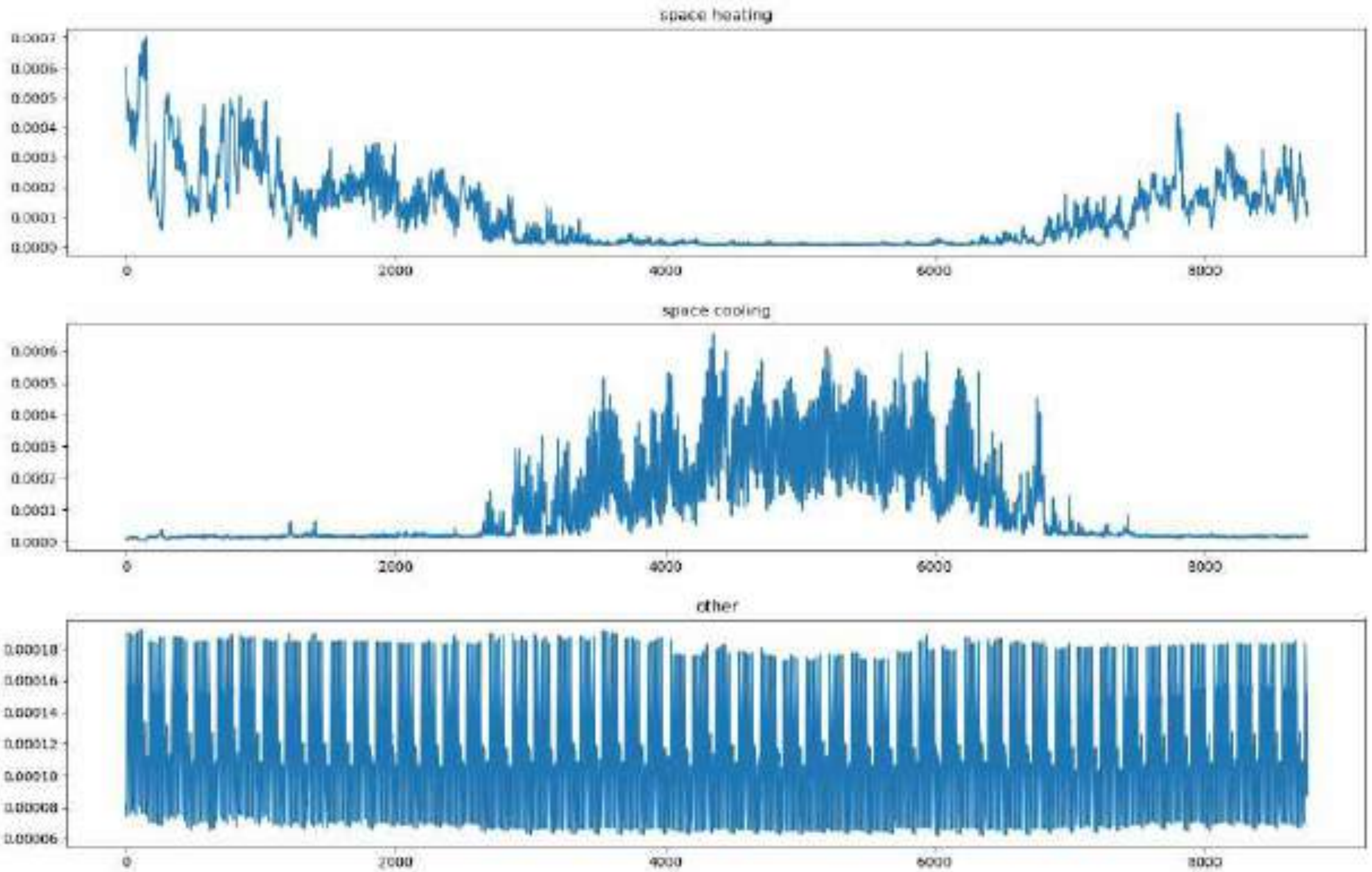
Hourly demand profiles for buildings

Residential - Ontario



Hourly demand profiles for buildings

Commercial - Ontario



Annual capacity factor

$$Capacity \times ACF = Demand$$

- To determine new capacity needed, we have to know how efficiently capacity is being utilised.

- We know capital costs but we need typical activity factors – i.e., how much each heat pump is used?

For residential buildings:

- We have stock data and demand data (NRCan Energy Use Database) so we can work this out.

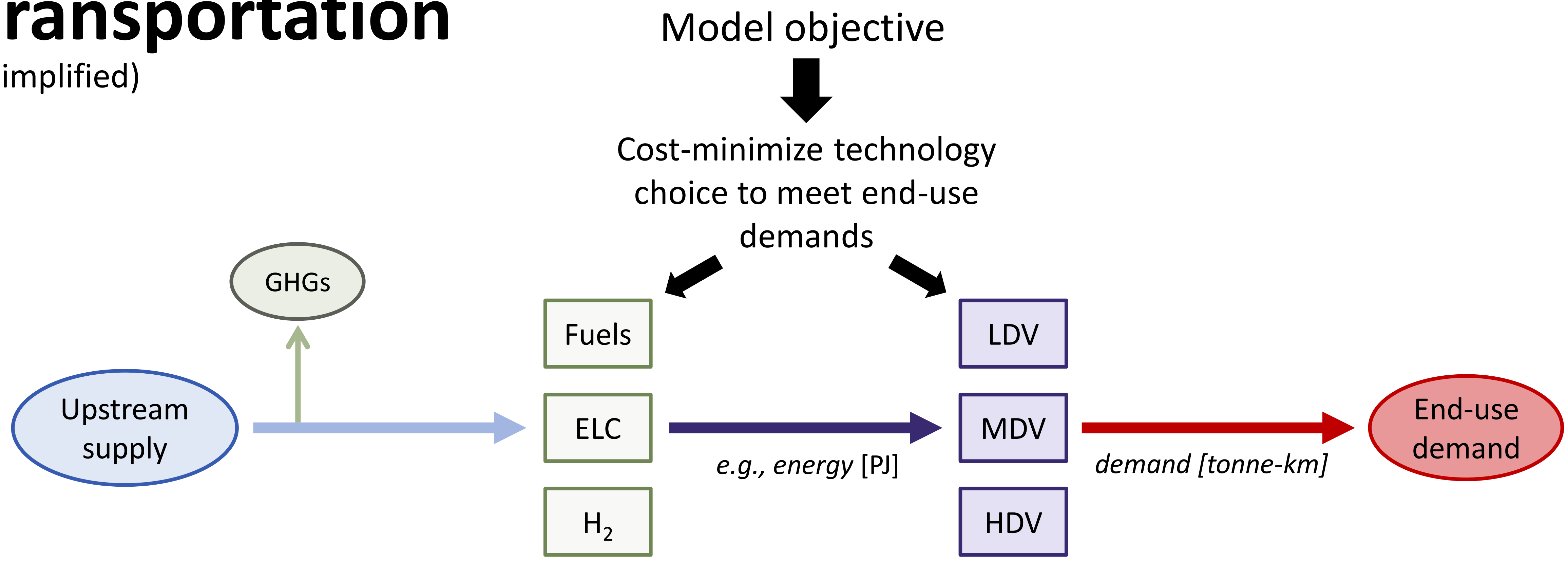
For commercial buildings:

- We have demand data (NRCan) but no stock data. For now, we assume perfectly sized (not realistic):

$$ACF = \frac{mean(demand)}{\max(demand)}$$

Transportation

(Simplified)



Technologies are parameterized by:

by: *Period*

Tech

Scenario

- Fuel prices
- Emission factors (fuel-cycle)
- Blend ratio

by: *Period* *Vintage*

Tech

Scenario *Powertrain*

- Existing capacity (by province)
- Efficiency
- Lifetime
- Investment costs
- Maintenance costs
- Emission factors (vehicle-cycle)

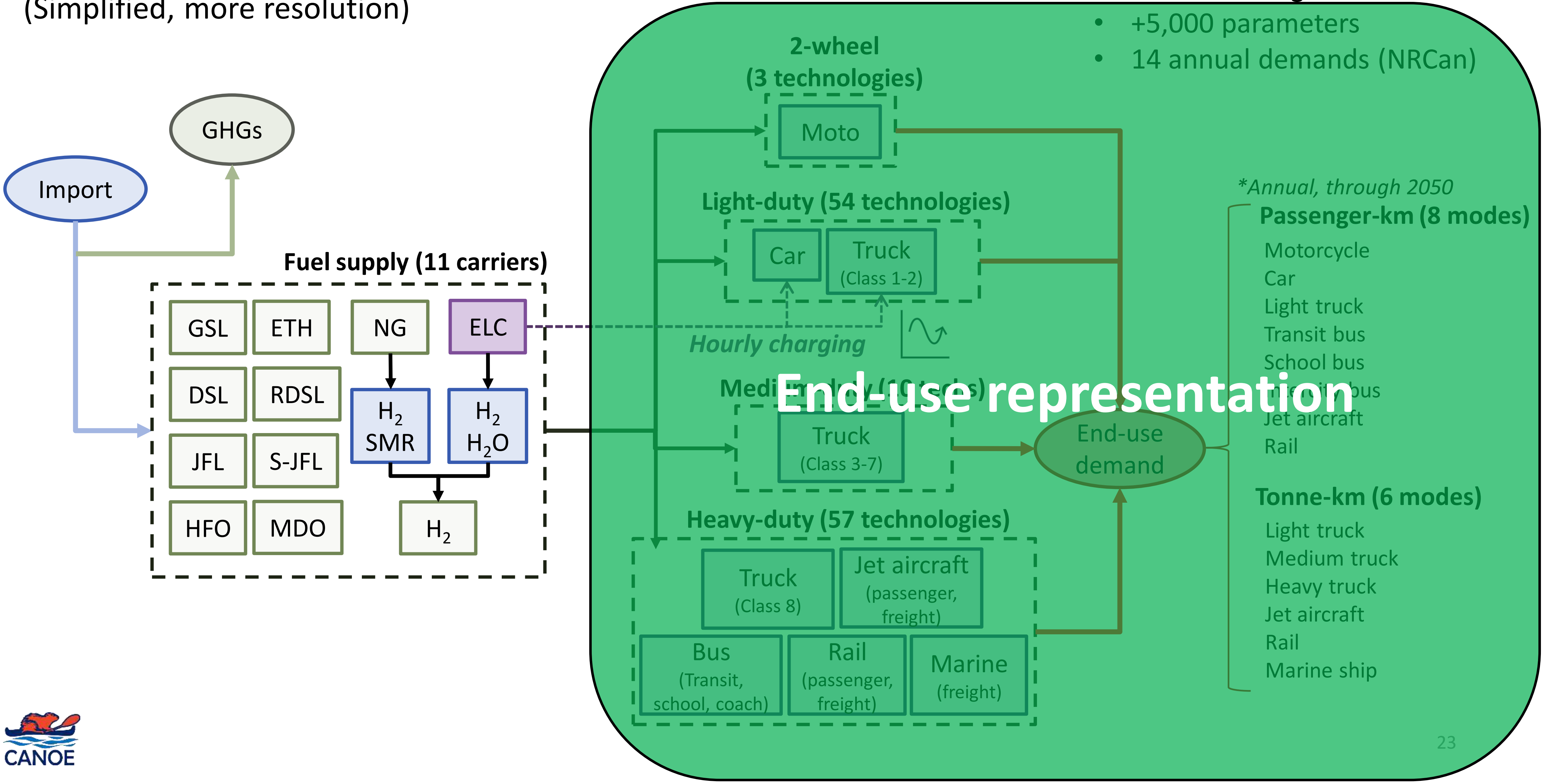
CANOE

Transportation

(Simplified, more resolution)

Overview of sector detail:

- 160 technologies
- +5,000 parameters
- 14 annual demands (NRCan)



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End-use representation and sources (Reference scenario → 2050)

Modes of transport	Fuel/Powertrain technologies (Parameters by powertrain, region, period and vintage)	Existing capacity (vehicle units or demand units)	End-use demand (passenger-km or tonne-km)	Technology lifetime (years)	Technology efficiency (demand unit/PJ)	Technology costs ($ CAD/capacity or activity unit)
Motorcycles	GASOLINE; BATTERY ELECTRIC	Natural Resources Canada *Comprehensive Energy Use Database (2022)*		E.I. Canada *EPS v3.0*	GCAM v7.0	GCAM v7.0
Cars	GASOLINE; DIESEL; COMP. NATURAL GAS; HYBRID ELECTRIC; PLUG-IN HYBRID ELECTRIC; BATTERY ELECTRIC; FUEL CELL ELECTRIC (H_2)			NHTSA *2022 CAFE model*	Islam et al., 2022. *(Autonomie tech. assessment)*	
Passenger Light Trucks	GASOLINE; DIESEL; COMP. NATURAL GAS; HYBRID ELECTRIC; PLUG-IN HYBRID ELECTRIC; BATTERY ELECTRIC; FUEL CELL ELECTRIC (H_2)					
Freight Light Trucks	GASOLINE; DIESEL; COMP. NATURAL GAS; HYBRID ELECTRIC; PLUG-IN HYBRID ELECTRIC; BATTERY ELECTRIC; FUEL CELL ELECTRIC (H_2)					
Medium Trucks	GASOLINE; DIESEL; COMP. NATURAL GAS; HYBRID ELECTRIC; PLUG-IN HYBRID ELECTRIC; BATTERY ELECTRIC; FUEL CELL ELECTRIC (H_2)					
Heavy Trucks	DIESEL; COMP. NATURAL GAS; HYBRID ELECTRIC; PLUG-IN HYBRID ELECTRIC; BATTERY ELECTRIC; FUEL CELL ELECTRIC (H_2)			EPA *MOVES4 model*		
School Buses	DIESEL; COMP. NATURAL GAS; HYBRID ELECTRIC; PLUG-IN HYBRID ELECTRIC; BATTERY ELECTRIC; FUEL CELL ELECTRIC (H_2)			Statistics Canada (2023)	Islam et al., 2022. *(Autonomie tech. assessment)*	
Transit Buses	DIESEL; COMP. NATURAL GAS; HYBRID ELECTRIC; PLUG-IN HYBRID ELECTRIC; BATTERY ELECTRIC; FUEL CELL ELECTRIC (H_2)					
Inter-City Buses	DIESEL; COMP. NATURAL GAS; HYBRID ELECTRIC; PLUG-IN HYBRID ELECTRIC; BATTERY ELECTRIC; FUEL CELL ELECTRIC (H_2)					
Passenger Air Transport	JET FUEL; SYNTHETIC JET FUEL (50%)	Natural Resources Canada *Comprehensive Energy Use Database (2022)*		Boeing, 2013. *Key Findings in Airplane Economic Life*	ANL *GREET 2022 model*	EPA *EPAUS9rT TIMES database (2019)*
Freight Air Transport	JET FUEL; SYNTHETIC JET FUEL (50%)					
Passenger Rail	DIESEL; HYDROGEN GAS (H_2); LIQ. NATURAL GAS			EPA *EPAUS9rT TIMES database (2019)*		
Freight Rail	DIESEL; HYDROGEN GAS (H_2); LIQ. NATURAL GAS					
Marine Freight	MARINE DIESEL; HEAVY FUEL OIL; LIQ. NATURAL GAS				*Transport Canada data w/GREET model*	*Open Energy Outlook 2022*
Off-road*	**Based only on current and projected demand.*	NRCan *EUD (2022)*				

Region
Ontario
Canada
US

Energy Innovation & Pembina Institute, 2023. *Canada Energy Policy Simulator v3.4.7.*
Environmental Protection Agency, 2023. *Population and Activity of Onroad Vehicles in MOVES4.* EPA-420-R-23-005.
Islam, E., Vijayagopal, R., & Rousseau, A., 2022. *A Comprehensive Simulation Study to Evaluate Future Vehicle Energy and Cost Reduction Potential.* Argonne National Laboratory, ANL/ESD-22/6.
National Highway Traffic Safety Administration, 2022. *CAFE Model 2022 Final Rule for Model Years 2024-2026 Passenger Cars and Light Trucks.*
Carnegie Mellon University - Wilton E. Scott Institute for Energy Innovation, 2022. *Open Energy Outlook for the United States.*
Mishra, G. S., Teter, J., Morrison, G. M., Yeh, S., Kyle, P., & Kim, S. H. (2013). *Transportation Module of Global Change Assessment Model (GCAM): Model Documentation* (UCD-ITS-RR-13-05). Institute of Transportation Studies, UC Davis.

Transportation

(Simplified, more resolution)

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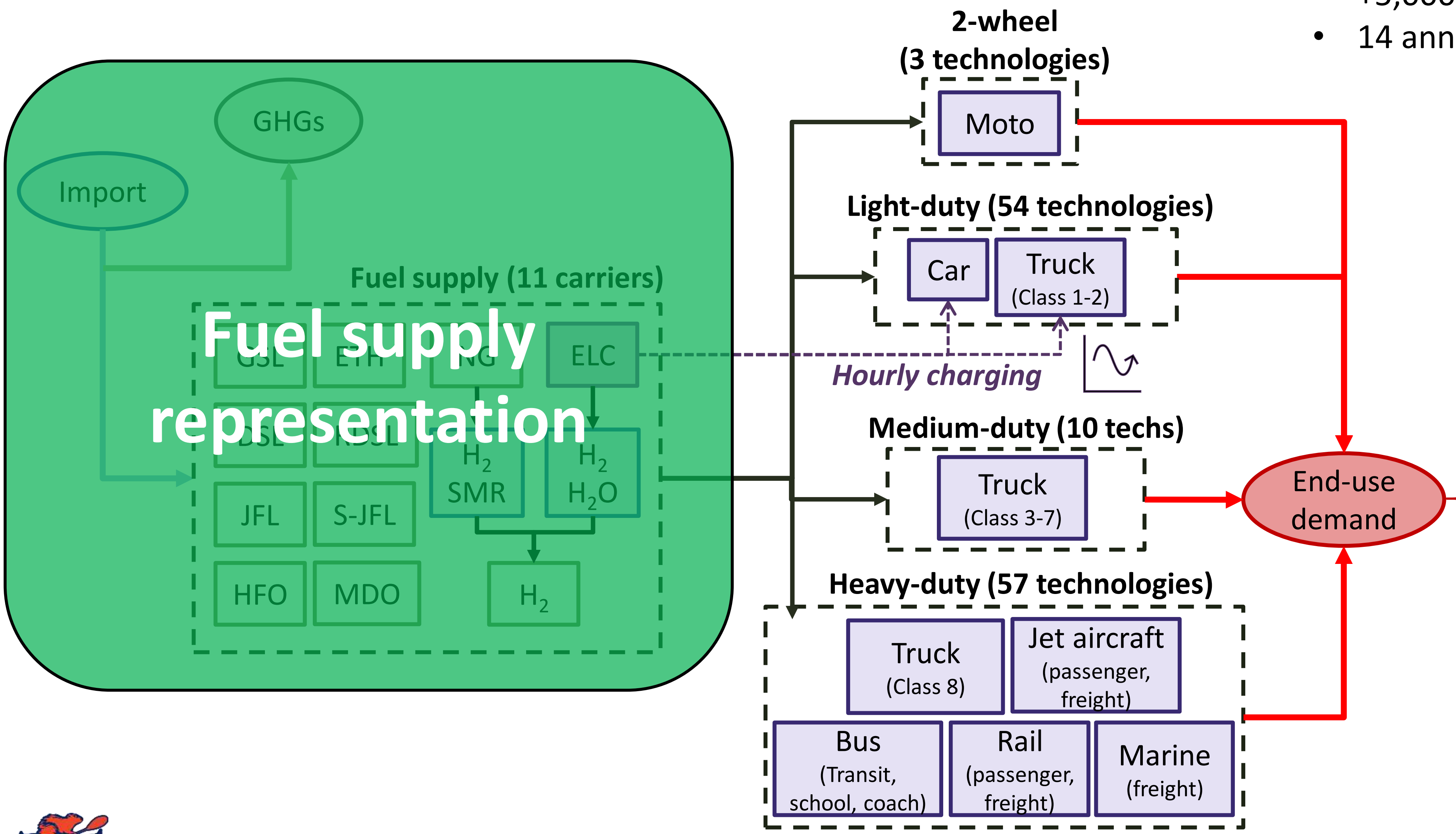

*Annual, through 2050

Passenger-km (8 modes)

Motorcycle
Car
Light truck
Transit bus
School bus
Intercity bus
Jet aircraft
Rail

Tonne-km (6 modes)

Light truck
Medium truck
Heavy truck
Jet aircraft
Rail
Marine ship

CANOE

Fuel supply representation and sources (Ref. scenario → 2050)

Energy carrier	Delivery method	Energy cost ($CAD/PJ)	Emission factor (g/HHV MJ)	Blending ratio (% vol)
Gasoline blendstock (BOB)	Direct import (no infrastructure constraints)	EIA *AEO 2023* Fuel prices from Mid-Atlantic Region	ECCC (2023) *Fuel LCA Model*	10% ethanol to 15% by 2030 (Cleaner Transportation Fuels)
Ethanol (corn)		Navius Research (2023) *Biofuels in Canada*	ANL *GREET 2023 model*	
Diesel	Direct import (no infrastructure constraints)	EIA *AEO 2023* Fuel prices from Mid-Atlantic Region	ECCC (2023) *Fuel LCA Model*	4% renewable content in diesel
Biodiesel & Ren. Diesel		Navius Research (2023) *Biofuels in Canada*	ANL *GREET 2023 model*	Assuming 50/50 biodiesel and HDRD based on sales data in ON.
Jet fuel	Direct import (no infrastructure constraints)	EIA *AEO 2023* Fuel prices from Mid-Atlantic Region	ECCC (2023) *Fuel LCA Model*	Available up to 50% SPK (ASTM standards)
Synthetic jet fuel (SPK)		NREL *Transportation ATB 2022*	ANL *GREET 2023 model*	
Natural gas (CNG & LNG)	Direct import (no infrastructure constraints)	EIA *AEO 2023* Fuel prices from Mid-Atlantic Region	ECCC (2023) *Fuel LCA Model*	
Marine diesel oil				
Heavy fuel oil				
Electricity	Endogenous, LDV and MHDV chargers	Electricity is imported from the electricity sector (prices and emissions are endogenous)		
H_2 gas	Endogenous, LDV and MHDV refuelling stations (@700 bar)	Simplified H_2 production pathways; SMR & electrolysis (technology parameters from OEO 2022)		

Region
Ontario
Canada
US

Carnegie Mellon University - Wilton E. Scott Institute for Energy Innovation, 2022. *Open Energy Outlook for the United States.*
Energy Information Administration (2023). *Annual Energy Outlook 2023—Table 3: Energy Prices by Sector and Source, Middle Atlantic Region, Reference case.*
Argonne National Laboratory (2023). *Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model ® (2023 Excel)* [Computer software]
Environment and Climate Change Canada. (2023). *Fuel Life Cycle Assessment Model.* (En4-418/3-2023E-PDF)
Michael Wolinetz & Sam Harrison. (2023). *Biofuels in Canada 2023: Tracking biofuel consumption, feedstocks and avoided greenhouse gas emissions*. Navius Research.

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Transportation

(Simplified, more resolution)

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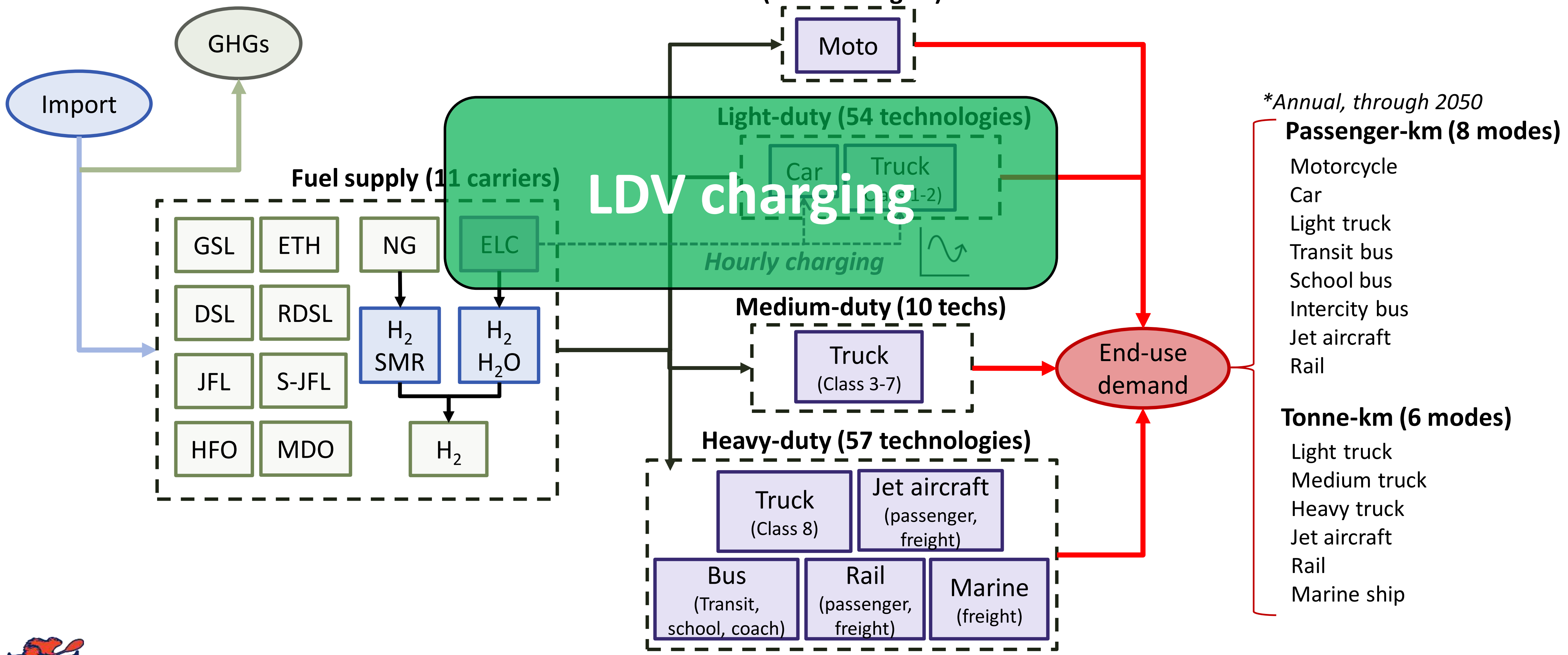
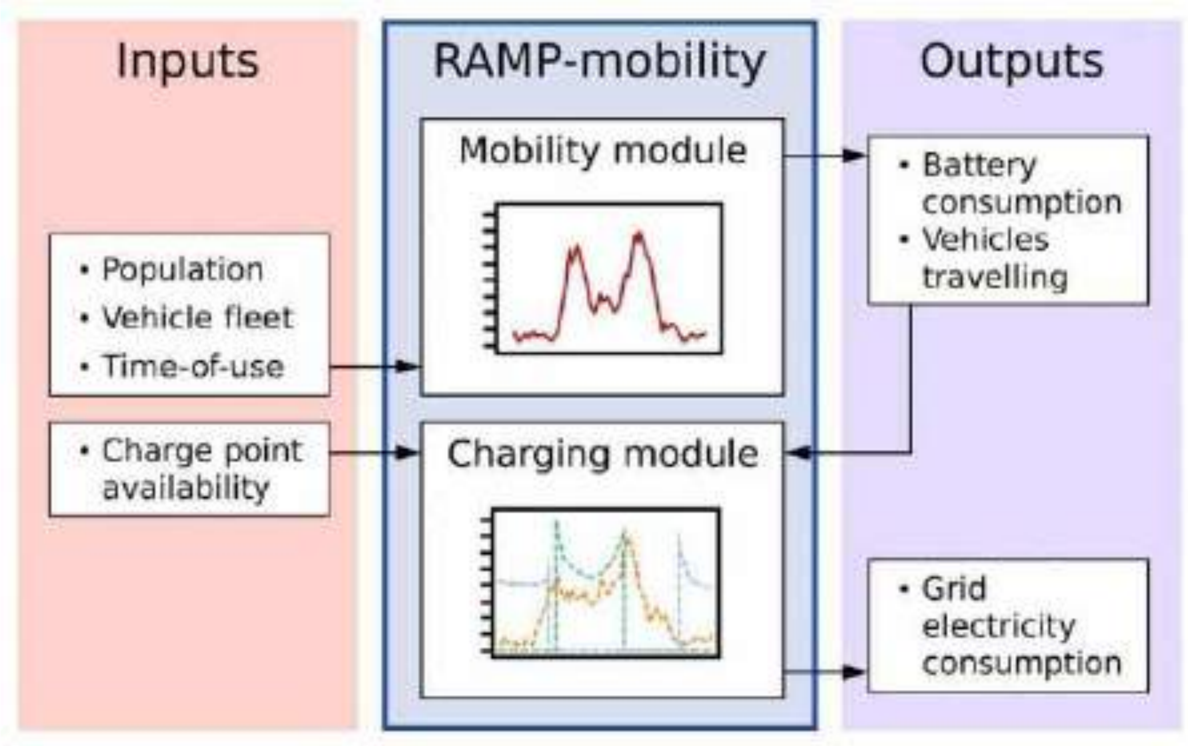


CANOE

Light-duty electric vehicle charging profiles

To capture the **short-term (hourly) variations** from light-duty EV charging demand:

→ We developed a **stochastic EV fleet aggregation** model using RAMP-mobility (by the Calliope team).



(Mangipinto et al. 2022)

Input parameter	Source
Population-weighted **temperature** (ON)	renewables.ninja (2018)
Trip characteristics and activity-travel schedules	Travel survey from GTHA (TTS 2016)
Battery EV **size** classes	Statistics Canada (2023)
Current and future battery **capacities**	Autonomie tech. assessment (2022)
Charging infrastructure **availability** (home vs. public)	ICCT charging assessment in Quebec (2022)
Charging usage by **type** (L1, L2, DCFC)	Pollution Probe charging experience survey (2024)

Mangipinto, A., Lombardi, F., Sanvito, F. D., Pavičević, M., Quoilin, S., & Colombo, E. (2022). Impact of mass-scale deployment of electric vehicles and benefits of smart charging across all European countries. *Applied Energy*, *312*, 118676.
Pollution Probe & Mobility Futures Lab. (2024). *2023 Canadian EV Charging Experience Survey*.
ICCT. (2022). Assessing charging infrastructure needs in Québec. *International Council on Clean Transportation*.

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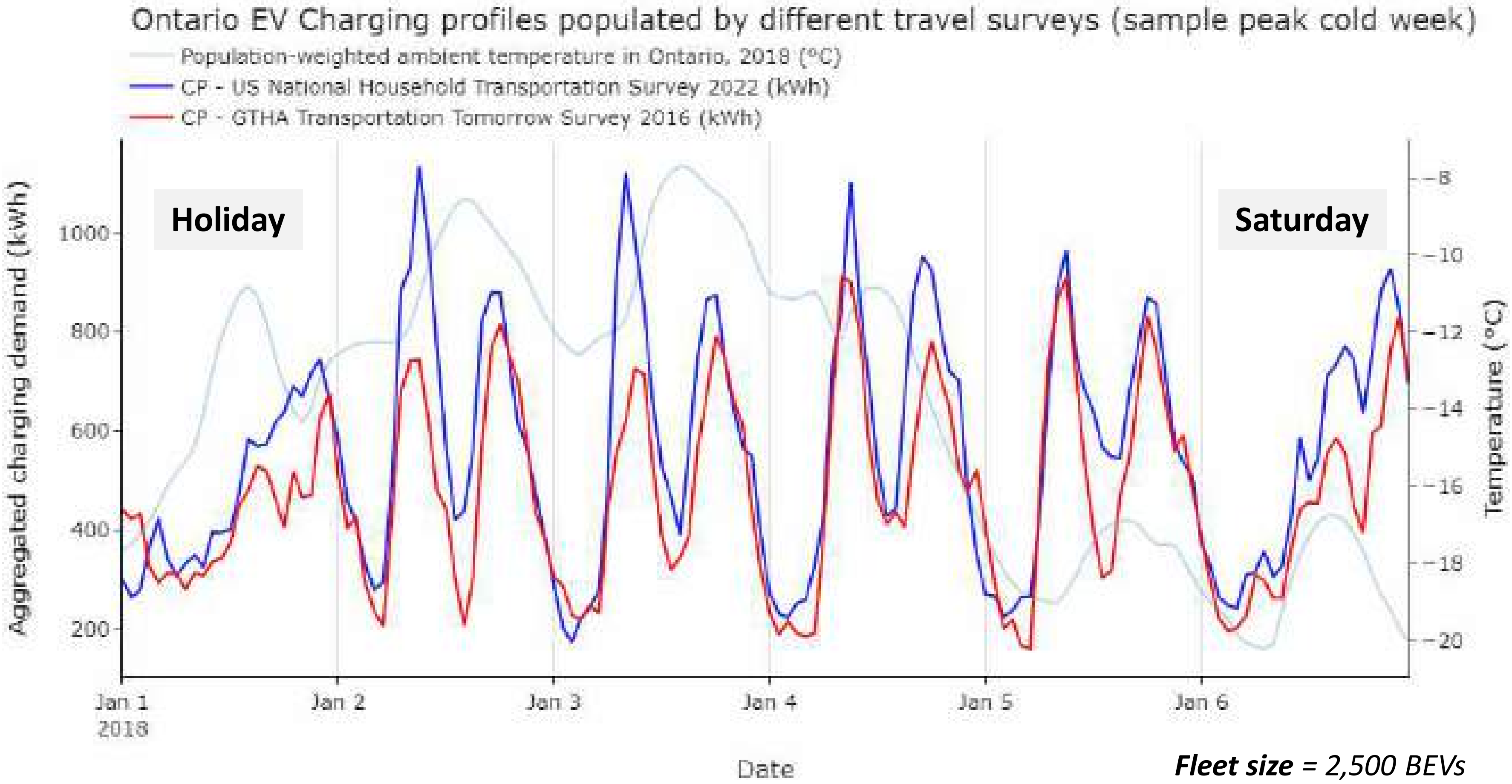

***Fleet size** = 2,500 BEVs*

<u>Limitations:</u> Canadian travel surveys are limited and exclusive to urban populations; no documentation of seasonal variations in travel.

Ongoing and future work in the transport sector

- Hourly charging demand from electric medium- and heavy-duty vehicles
- Urban transit modes (subways & streetcars)
- Expanded fuel representation e.g.,
  - E-fuels
  - Realistic petroleum sector constraints
- Passenger travel in other regions,
  - …including those lacking travel surveys

- Limitations (maybe long-term future work?)
  - Behavioural realism
  - No representation of market heterogeneity (vehicle choice)
  - No representation of end-user mobility choices (modal choice)

CANOE

Progress to date

- Lots of data collection and setting up workflows + core modeling choices
- Skeleton model nearly complete (Ontario and Alberta)
- Sector model representations in progress:
  - Preliminary representation of electricity (Ontario and Alberta)
  - Simplified representation of residential buildings (Ontario)
  - Draft of detailed transport sector for Ontario
    - Working on Generalizability
  - Ongoing work on detailed industrial representation – starting with Oil & Gas sector (Alberta)
    - On deck: Cement and Steel (Alberta and Ontario)

- Major future steps
  - Finalize detailed representations for focus sectors
  - Generalize model to rest of Canada
  - Release simplified public model / database
    - Still multiple months away
  - Connect with other TEMOA branches (e.g., US, Atlantic Canada) and novel functionalities (e.g., LCA & MFA)

CANOE

Thank you

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https://sustainablesystems.civmin.utoronto.ca/canadian-open-energy-canoe-model/

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