# Modeling multisectoral interactions in the TEMOA Canadian Open Energy Model (CANOE)


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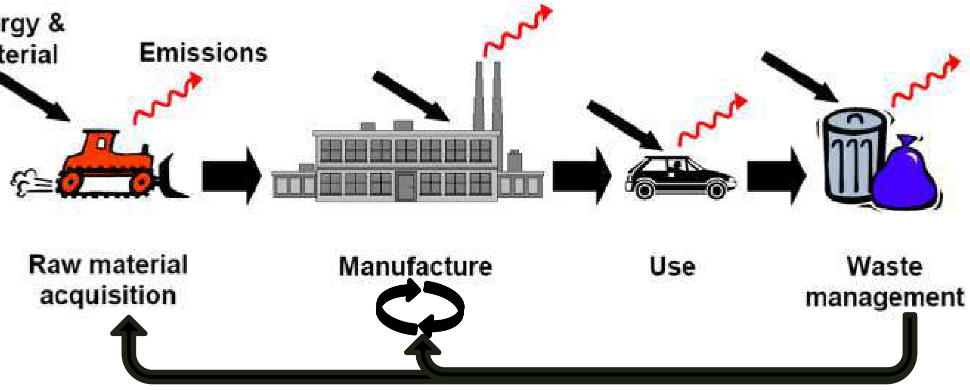
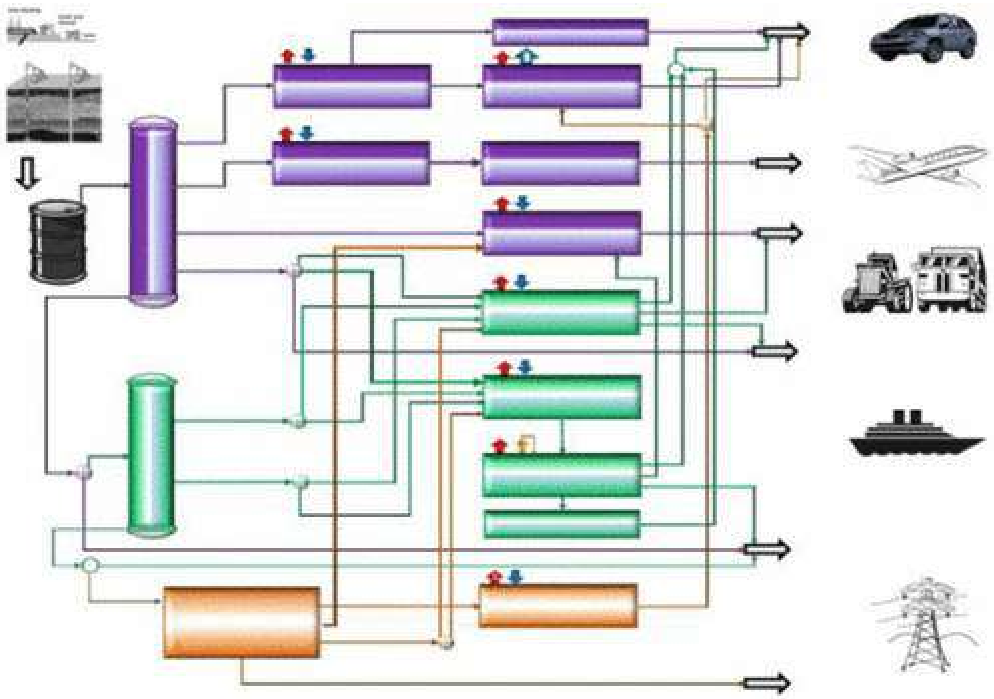
University of Toronto · University of Calgary · University of Waterloo · University of Alberta

# Our team comes from diverse areas adjacent to energy modeling

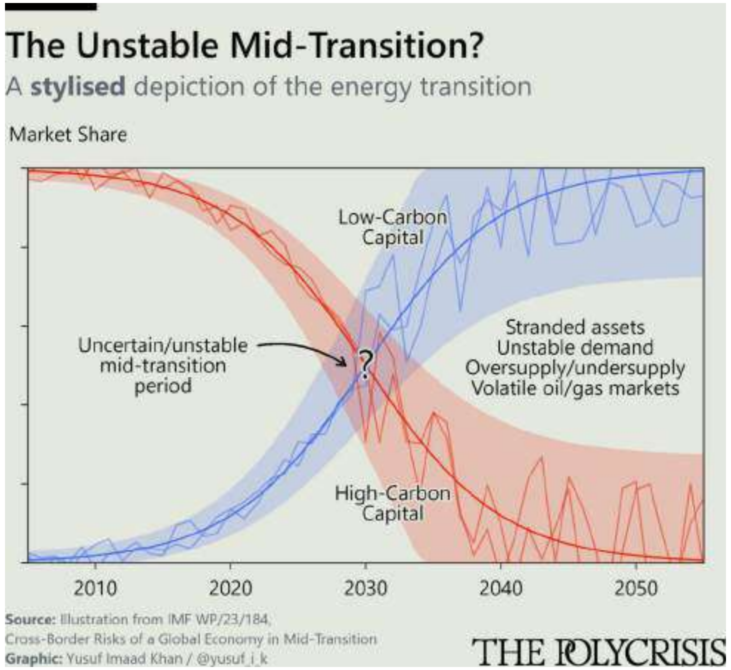
**Life cycle assessment and Material flow analysis**




**Detailed technology modeling (e.g., refineries)**



*Abella and Bergerson 2012; Prelim model (updated 2022)*



# CANOE is a capacity expansion ESOM

**Classification**

- Energy systems optimisation model (LP)
- Least-cost capacity expansion
- Built on **new Temoa v4.0**

**Spatial resolution**

- **National-provincial** (one region per province)

**(Typical) Temporal resolution**

- 5-year periods, **2025 to 2050** (maybe 2070)
- Representative days with **hourly resolution**

**Supply sectors**

- Chemical fuels (liquid, gaseous fuels)
- Electricity

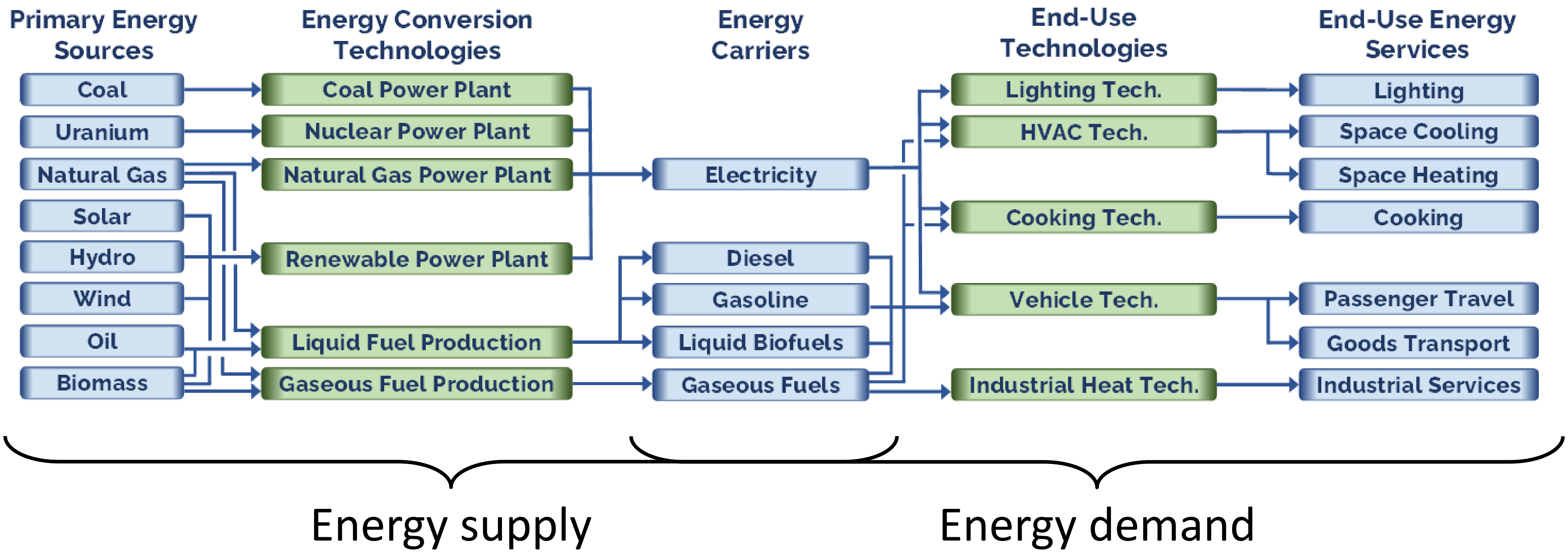
**Demand sectors**

- Industry
- Transportation
- Buildings

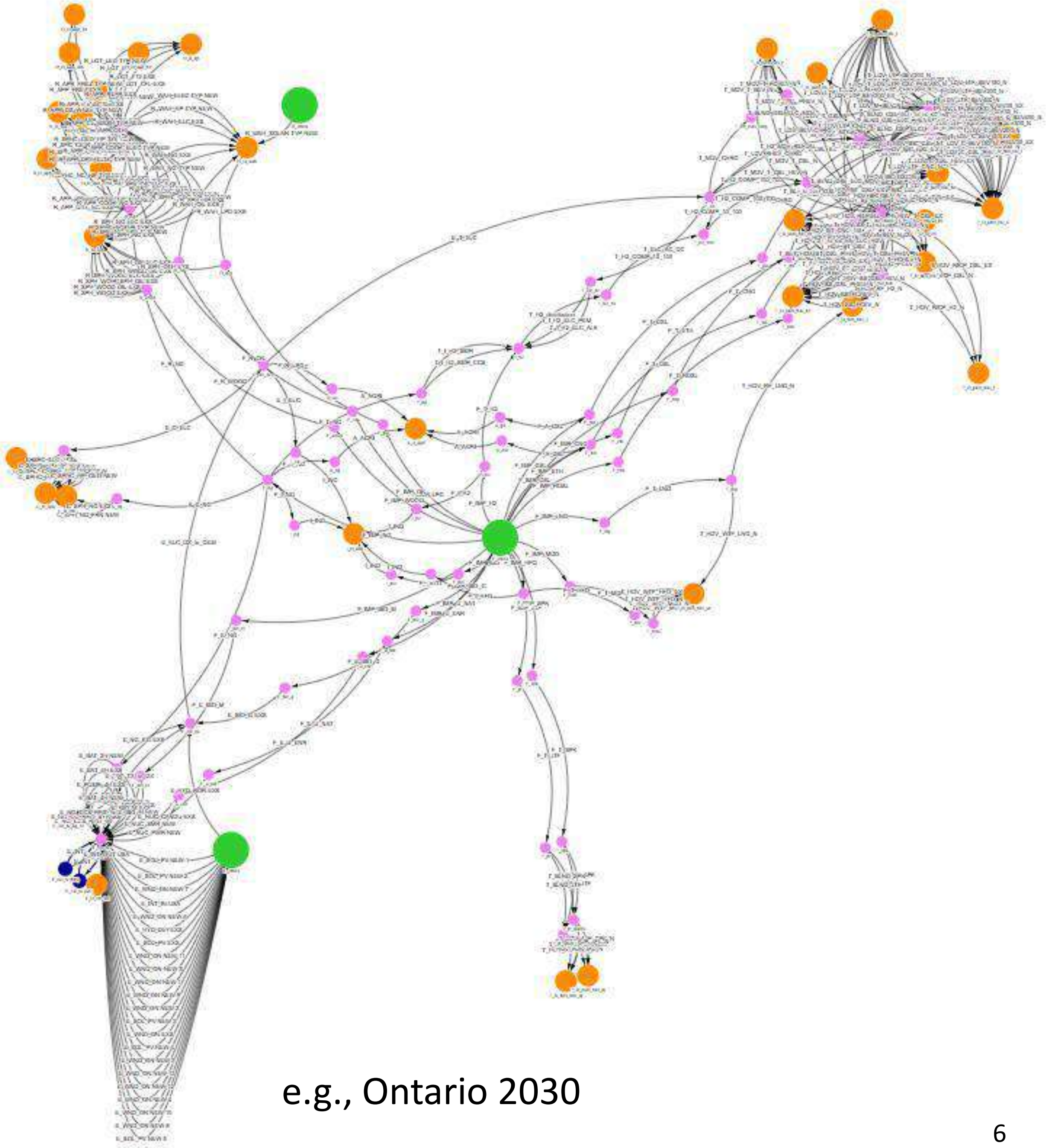
(Also carbon removal, e.g. direct air capture)

# Systems representation – CANOE

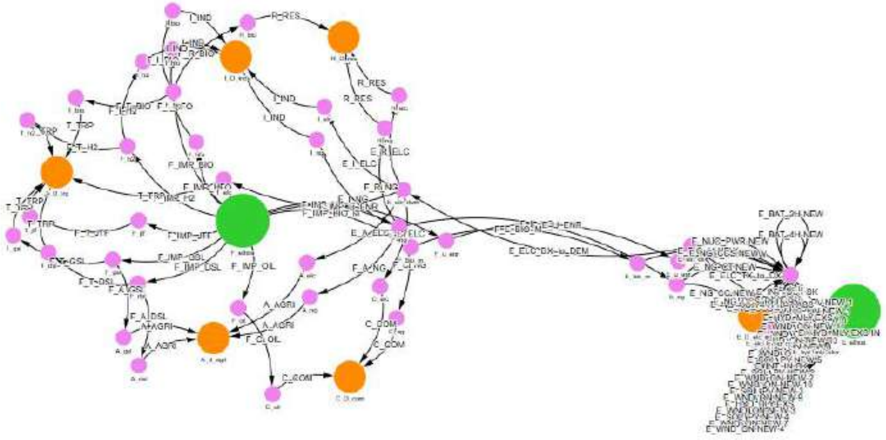
*(demonstrative subset of systems)*



# Snapshots of the real network



e.g., Ontario 2030



e.g., Manitoba 2050

# Building CANOE

*Managing an open source, multi-sectoral ESOM*

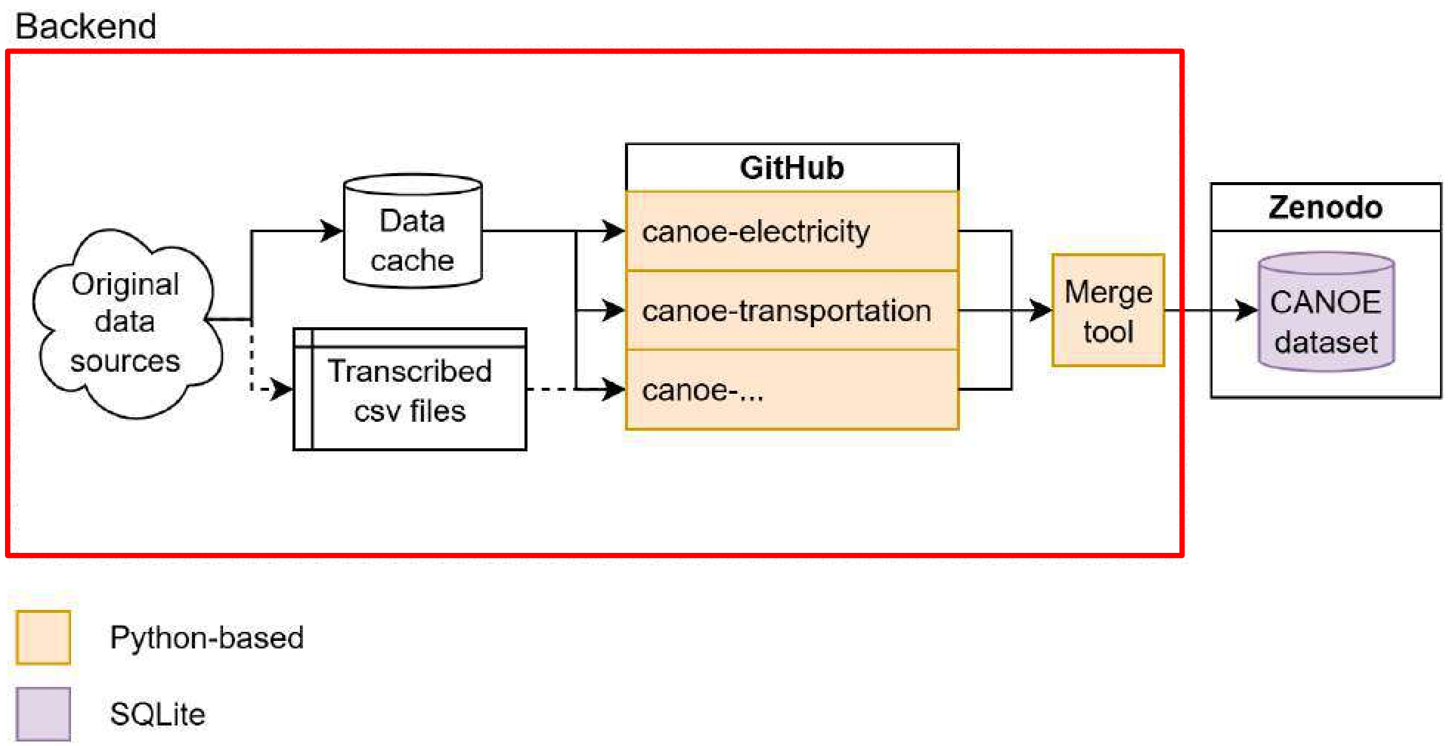
## Problem

**Huge amount of data.** How do we mitigate input errors, keep track of assumptions and document all processing steps?

## Solution

**Python.** Build the database via code, never manually edit data. Publish Python scripts on GitHub for transparency and collaboration.

# Building CANOE




Mastermind: Davey Elder

# Building CANOE

*Managing an open source, multi-sectoral ESOM*

## Problem

**Huge amount of data.** How do we mitigate input errors, keep track of assumptions and document all processing steps?

**Model complexity.** How do we model Canada's entire energy system but also tackle smaller research questions and explore uncertainty?

## Solution

**Python.** Build the database via code, never manually edit data. Publish Python scripts on GitHub for transparency and collaboration.

**Modularity.** Construct each region, sector, and feature modularly with unique data IDs. Filter by these IDs to model only what you're interested in.

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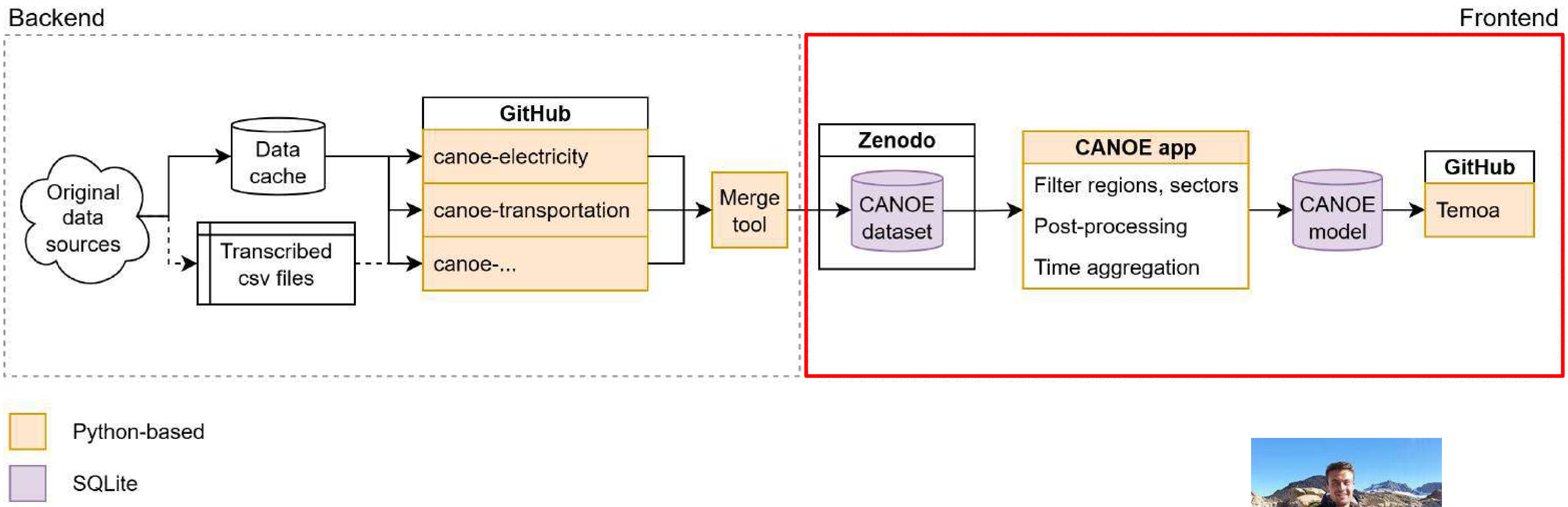
# Building CANOE

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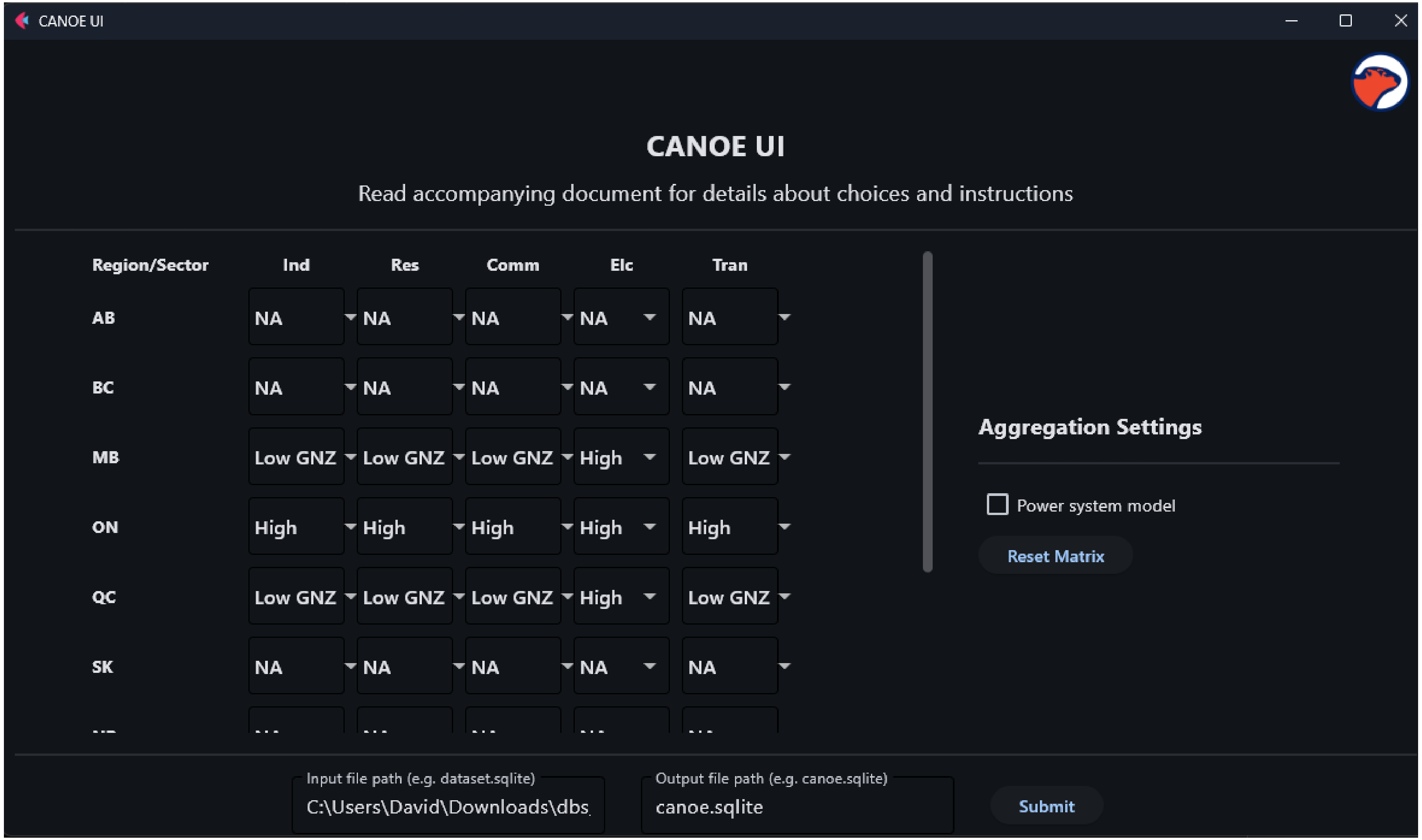
# Model resolution selection




David Turnbull

# New model features in CANOE / Temoa

## Embodied carbon

Full life cycle emissions accounting

## Endogenous material flows

Critical minerals

Bulk materials

## EV charging

Charging infrastructure for electric vehicles

Charging behaviours (hourly charging demand)

## Oil refineries

Constraining realistic petroleum product fractions

## Seasonal storage

Hydroelectric reservoirs

E-fuels, hydrogen

## Endogenous technological learning

Declining capital costs with greater deployment

## Survival curves

Realistic technology survivorship

## Growth rate constraints

Realistic technology deployment and phaseout



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# Embodied carbon

*Full lifecycle emission accounting*

Cameron Wade

- Most frameworks account for operational emissions, indexed to energy flows.
- We now also account for embodied emissions, indexed to construction and end of life of technology capacity.
- Accounts for all upstream and downstream lifecycle emissions.
- Not just emissions. Can also be land use, job creation, etc.

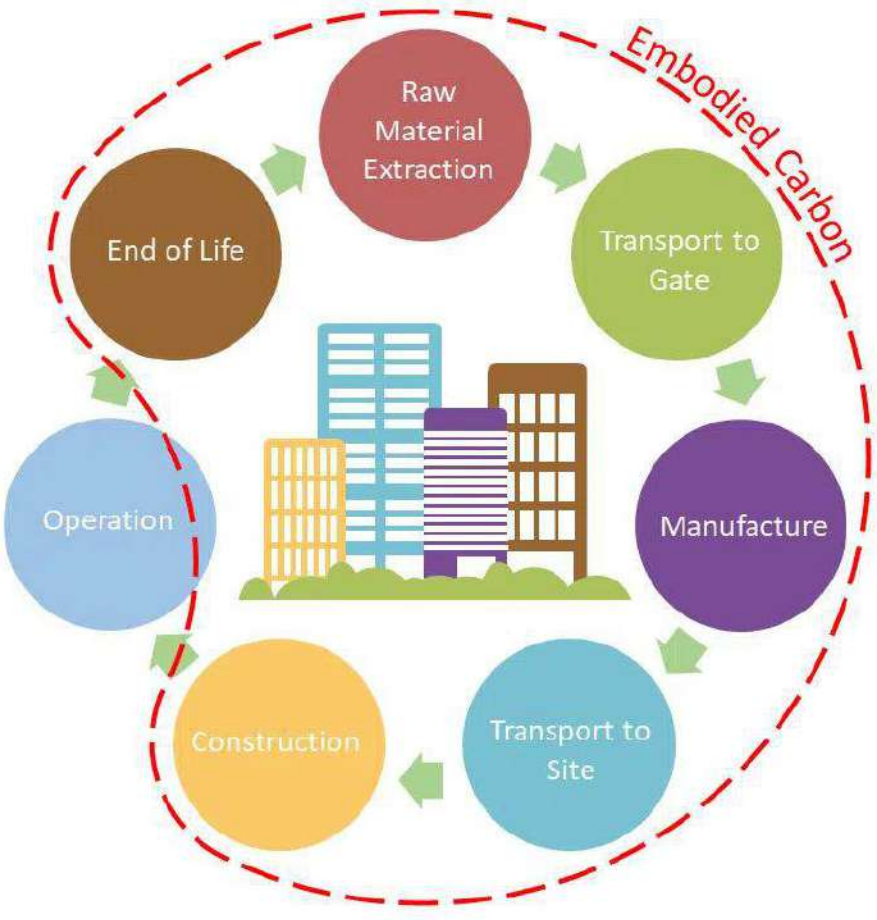


Figure from https://circularecology.com/embodied-carbon-footprint-database.html

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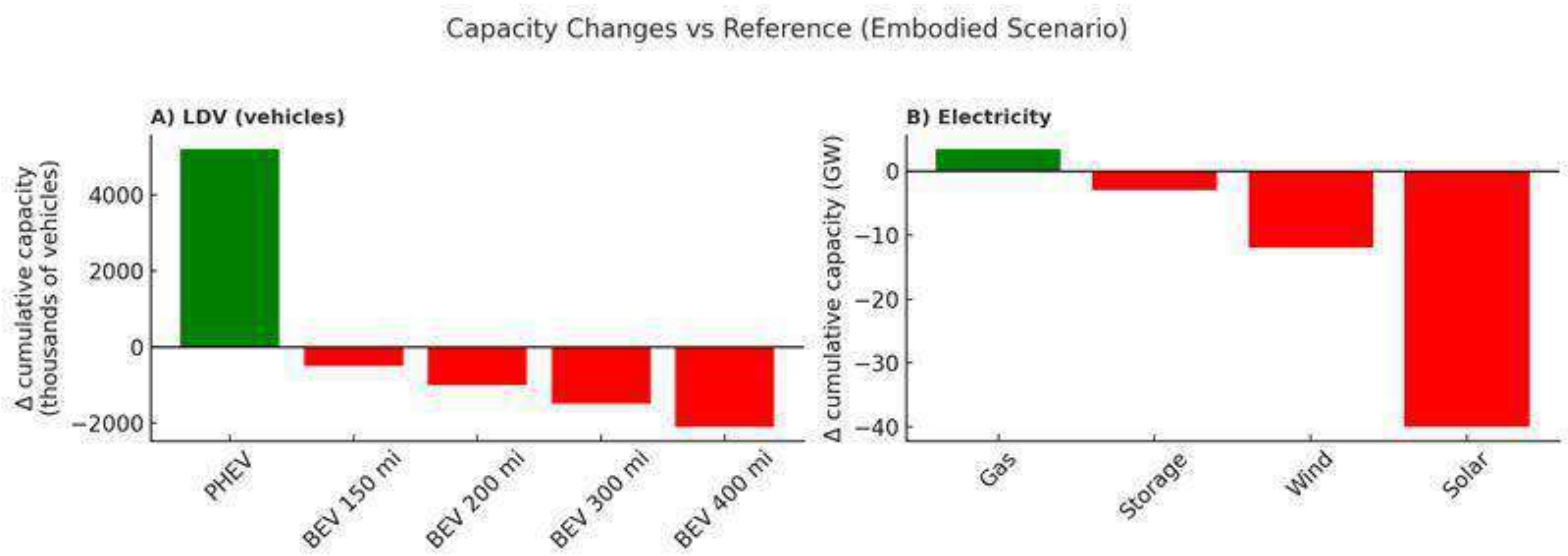
# Embodied carbon

*Change in multiple sectors when accounting for embodied emission costs*




Shahid Hossaini

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# Endogenous material flows

*Endogenous process flows indexed to technology capacity*

Davey Elder

- Connect construction and end of life of technologies to commodity flows in the process network.
- Track supply chains and recycling for bulk materials (steel, concrete, ...), critical minerals (lithium, cobalt, ...), or components (e.g., batteries).
- Endogenously model energy consumption of these supply chains.

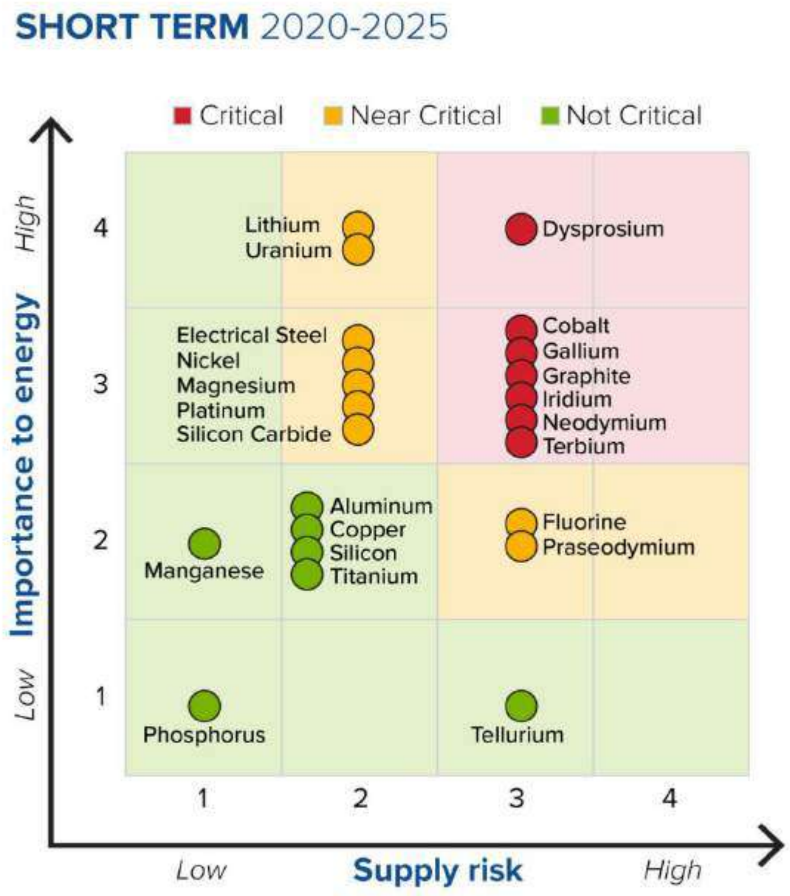


Figure from DOE https://www.energy.gov/cmm/what-are-critical-materials-and-critical-minerals

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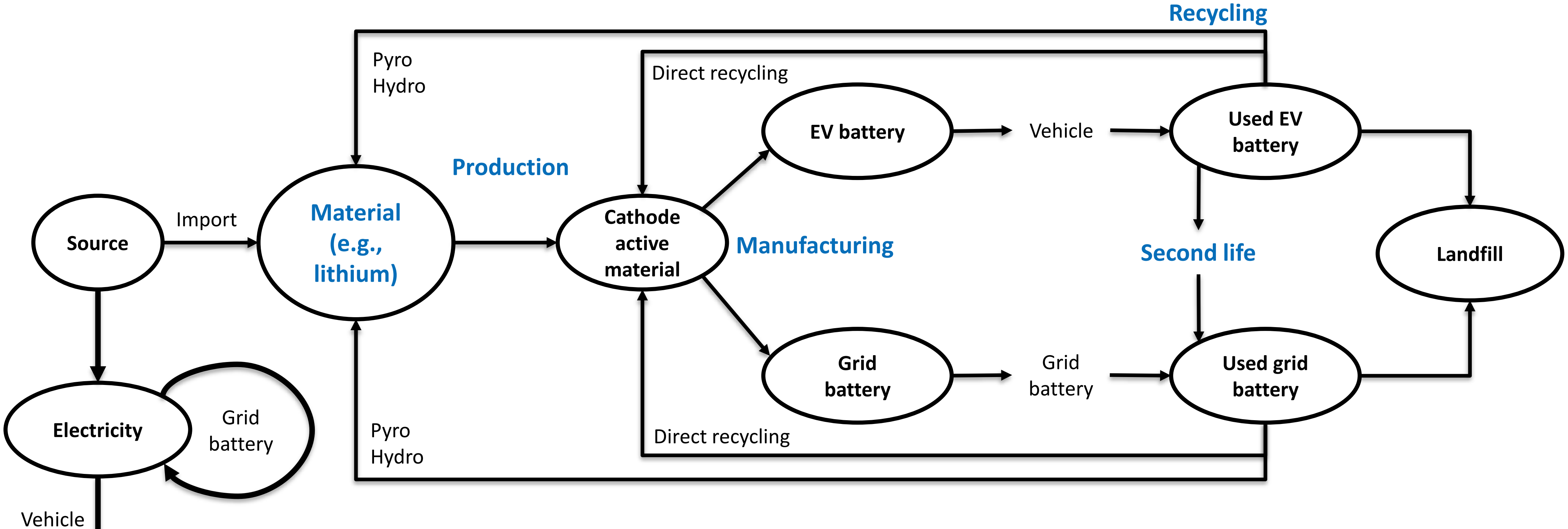
# Endogenous material flows

*Application: battery supply chains*




Dijuan Liang

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# Heavy duty EV truck charging

*Demand profiles from GPS data + Charging infrastructure technology choice*

**Simulate charging profiles**

- Truck **GPS data** (2019, Ontario)
- Truck activity **schedules**
- Battery / tank capacity
- **Weather** conditions

→ **Hourly energy demand** profiles for HDTs

→ **CANOE Ontario**

- Electricity production
- $H_2$
- Storage
- **Heavy duty trucking technology choice**
- Freight demand
- Time series aggregation

→ **Outputs**

- **Optimal technology mix**
- Wind/solar curtailment
- System cost
- GHG emissions

Sebastian Villada Rivera



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# Heavy duty EV truck charging

*Spatially explicit E-road expansion*


Lih Wei Yeow

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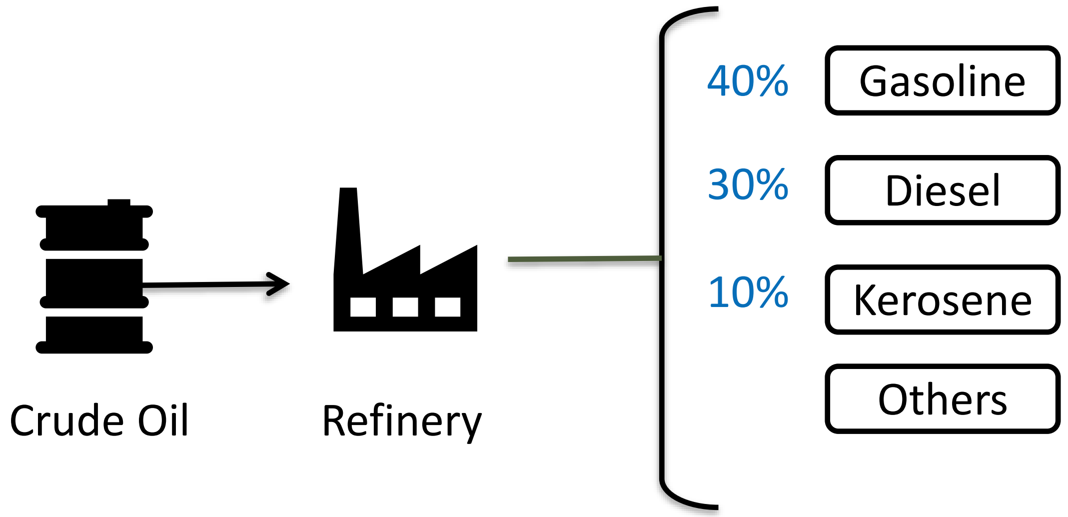
# Oil refineries

*Constraining realistic product fractions*

- Oil refineries are designed to produce a particular ratio of output products.
- Can we phase out one fuel at a time? (e.g., gasoline but not diesel)
- Model oil refineries to explore constraints due to refinery design and operation.



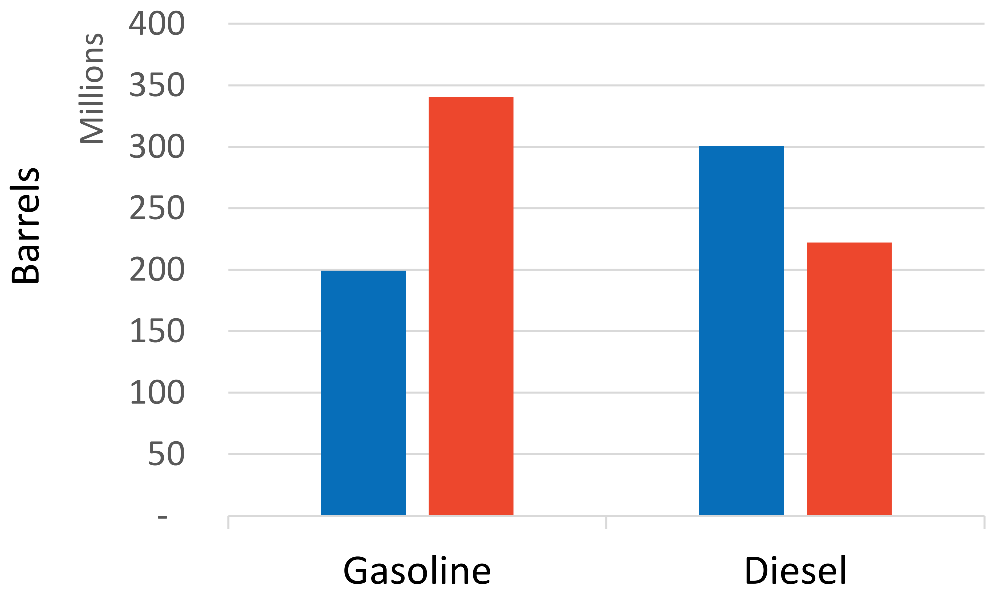

Thiago Rodrigues

# Oil refineries: constraints on product mix may slow light-duty vehicle electrification (or speed up truck electrification)

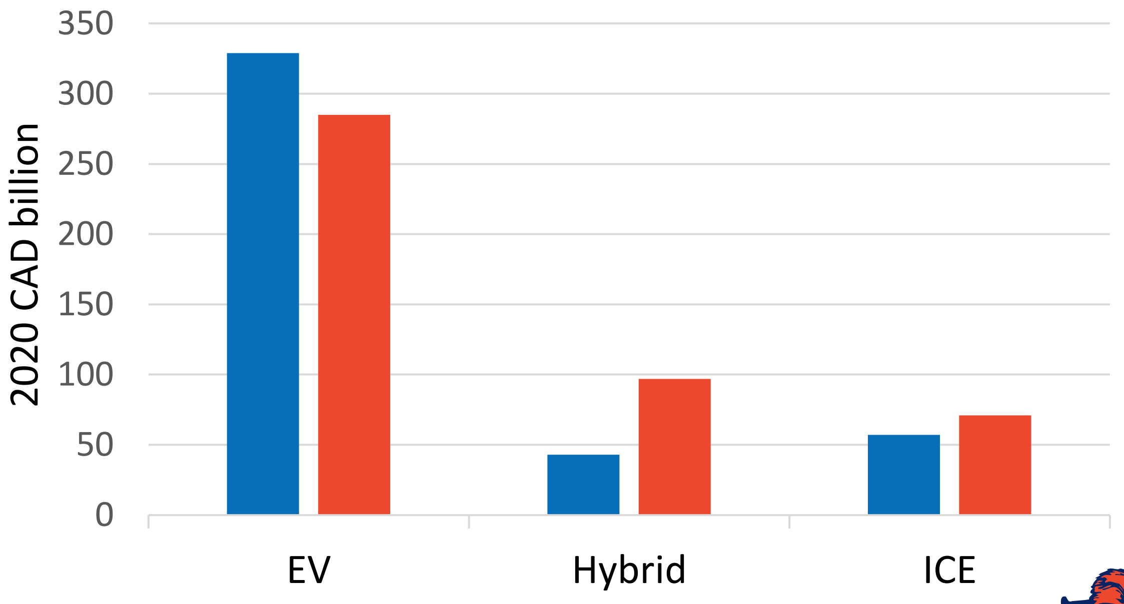
*Testing results: before and after forcing existing product ratios*

**Scenario:** **Free product ratios** **Fixed product ratios**

**Fuel consumption (2025 – 2050)**




**Investments in new vehicles (2025 – 2050)**





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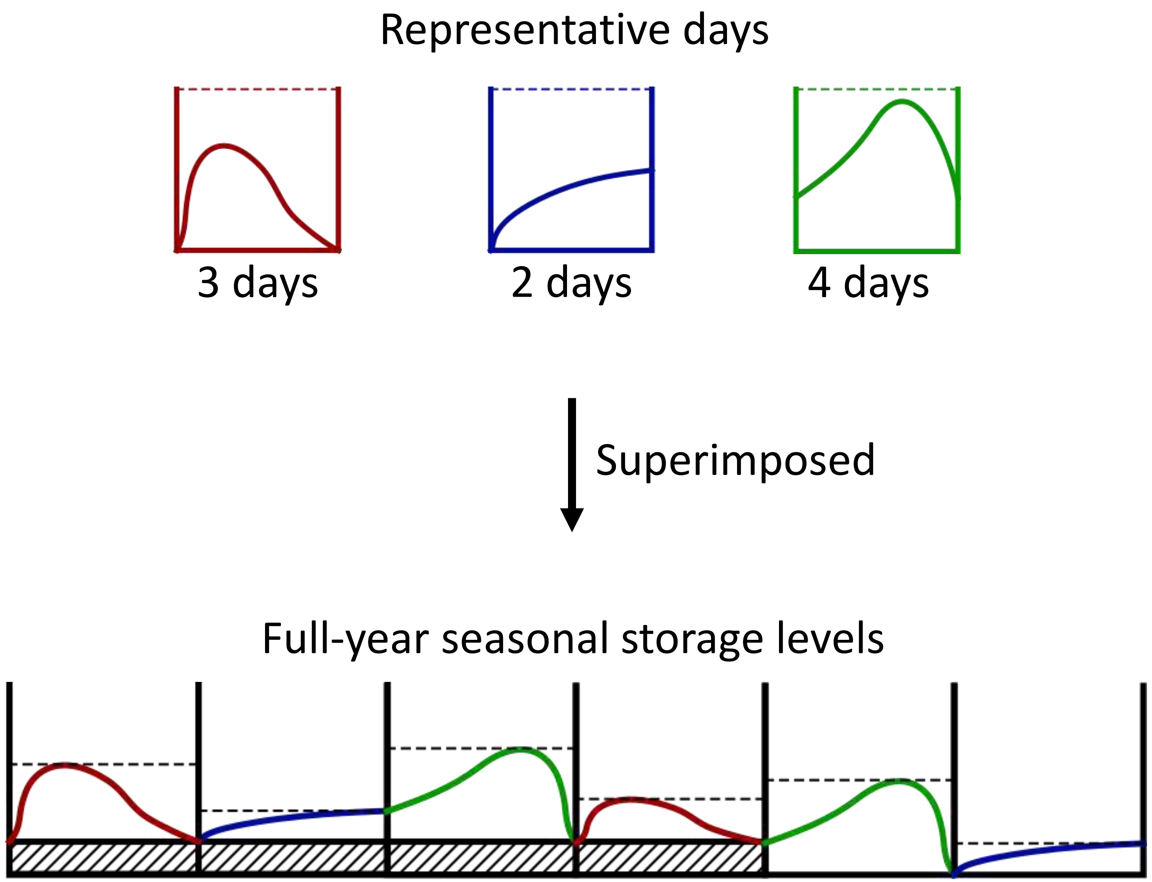
# Seasonal storage

*Long duration storage in a time-aggregated model*

Cameron Wade

Davey Elder

- Many energy models use seasonal time slicing or representative days to reduce the time dimension.
- Broken chronology leads to irrational inter-seasonal storage behaviour.
- We reconstruct the original sequence of our base weather year from these representative days. Restoring rational seasonal storage behaviour.
- Applies to large-reservoir hydroelectric, E-fuels, hydrogen.

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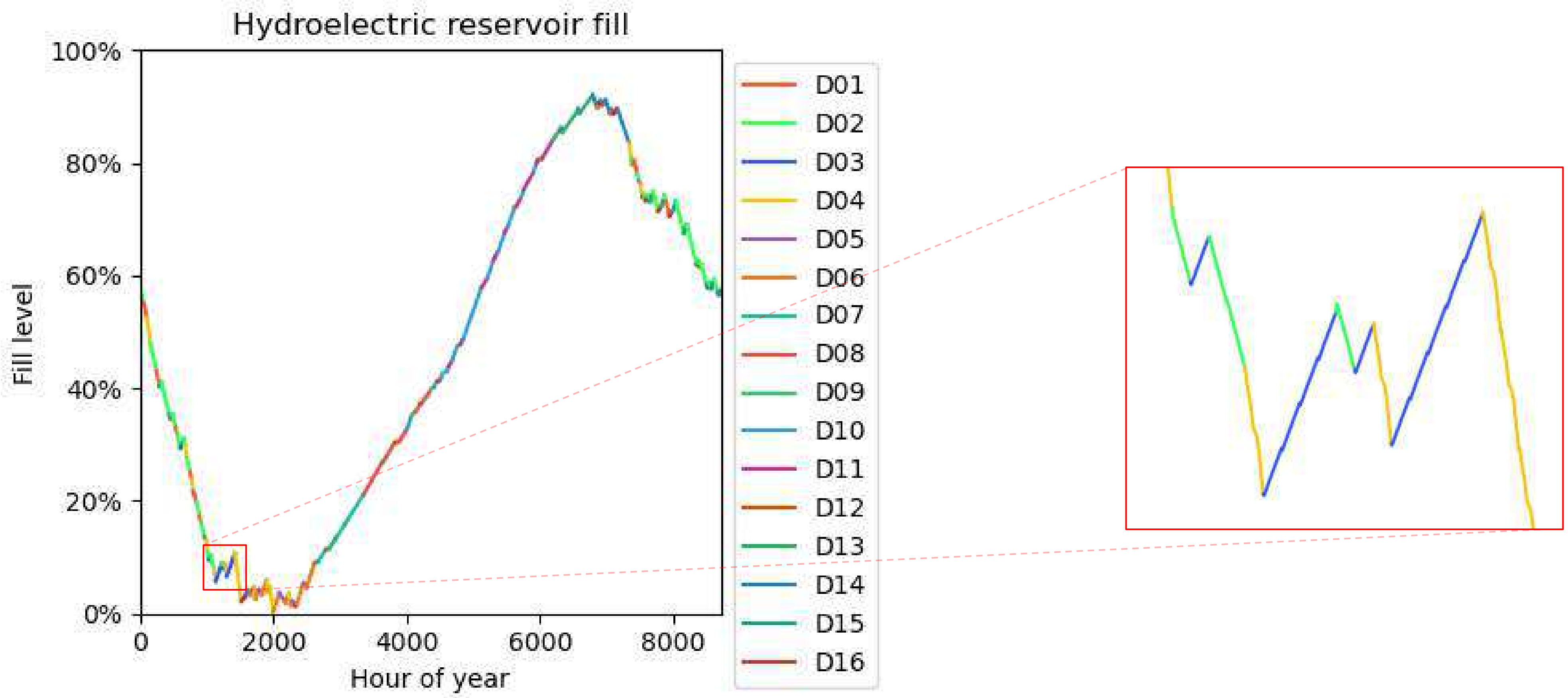
# Seasonal storage

*Example: Sixteen representative days. Hydroelectric reservoirs in Manitoba, 2050.*



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# Endogenous technological learning

*Declining capital costs with increasing cumulative production*

Davey Elder

- New technology costs usually decline over time due to economies of scale and innovation.
- We can endogenise declining capital costs using a mixed integer linear (MILP) formulation (based on TIMES).
- Our implementation is flexible to summation over regions and groups of technologies.

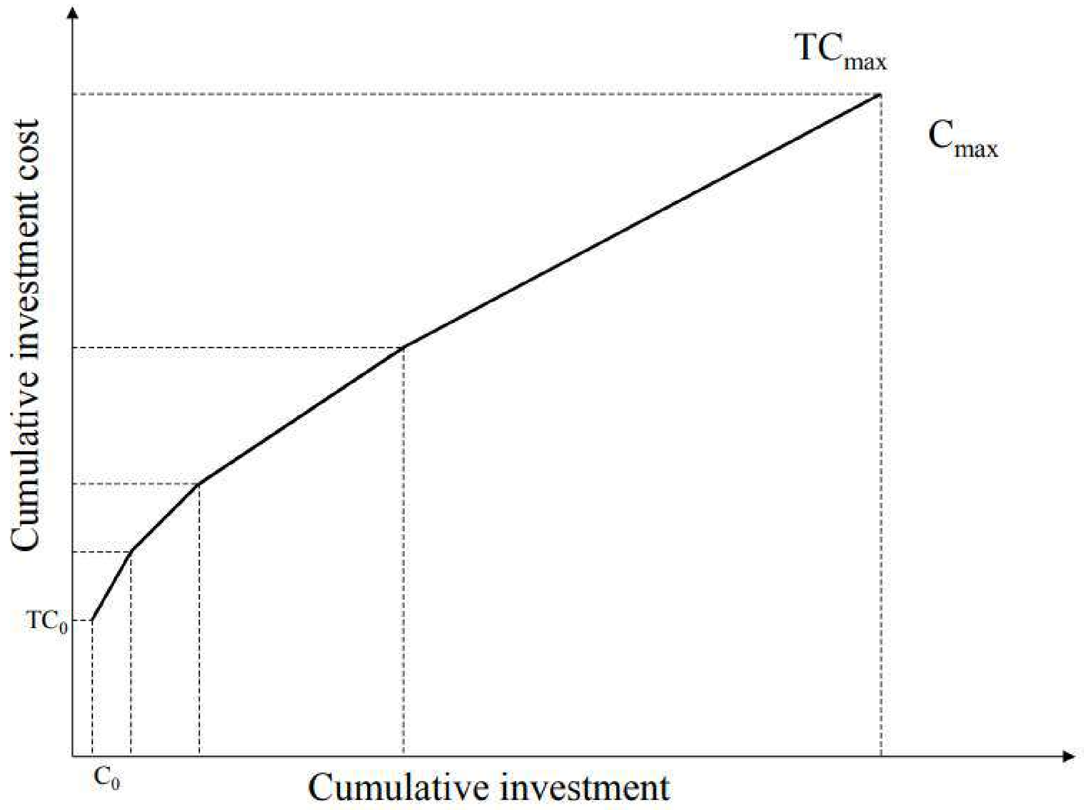


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Figure from TIMES documentation https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-I_July-2016.pdf

# Endogenous technological learning

*Application: emerging technologies*

Davey Elder

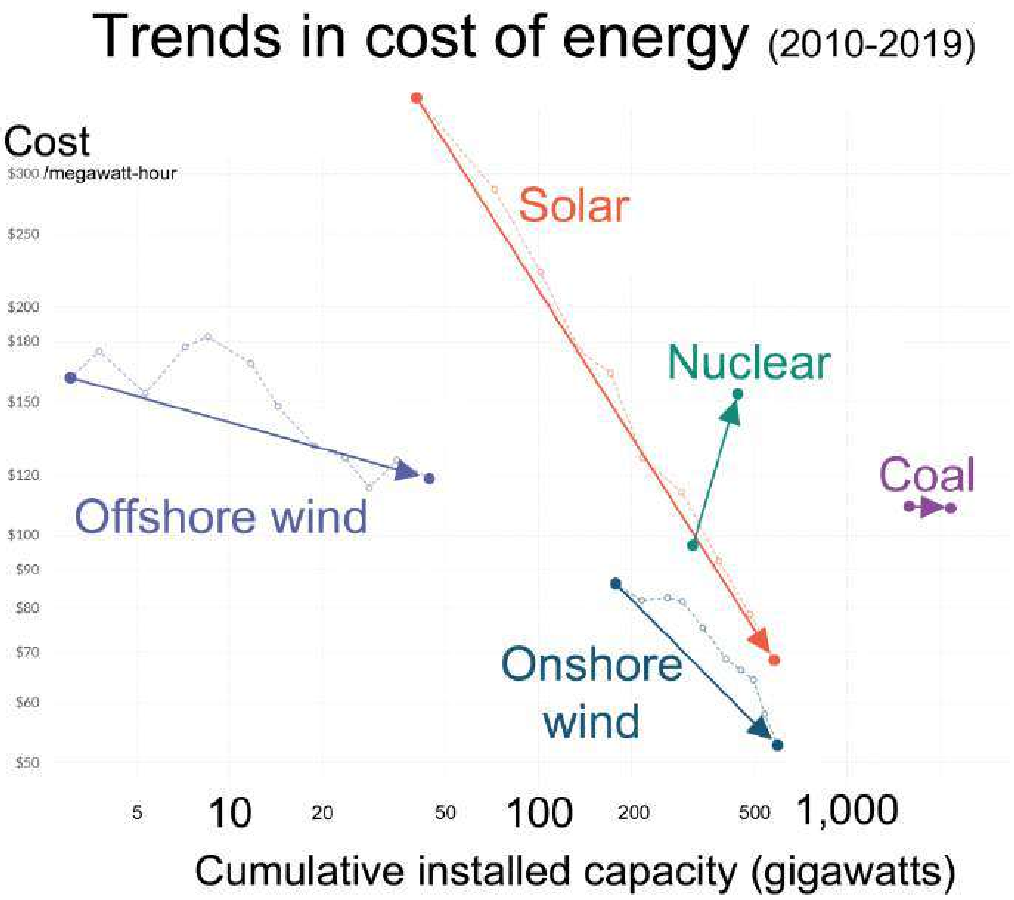


Figure from Our World In Data https://ourworldindata.org/cheap-renewables-growth



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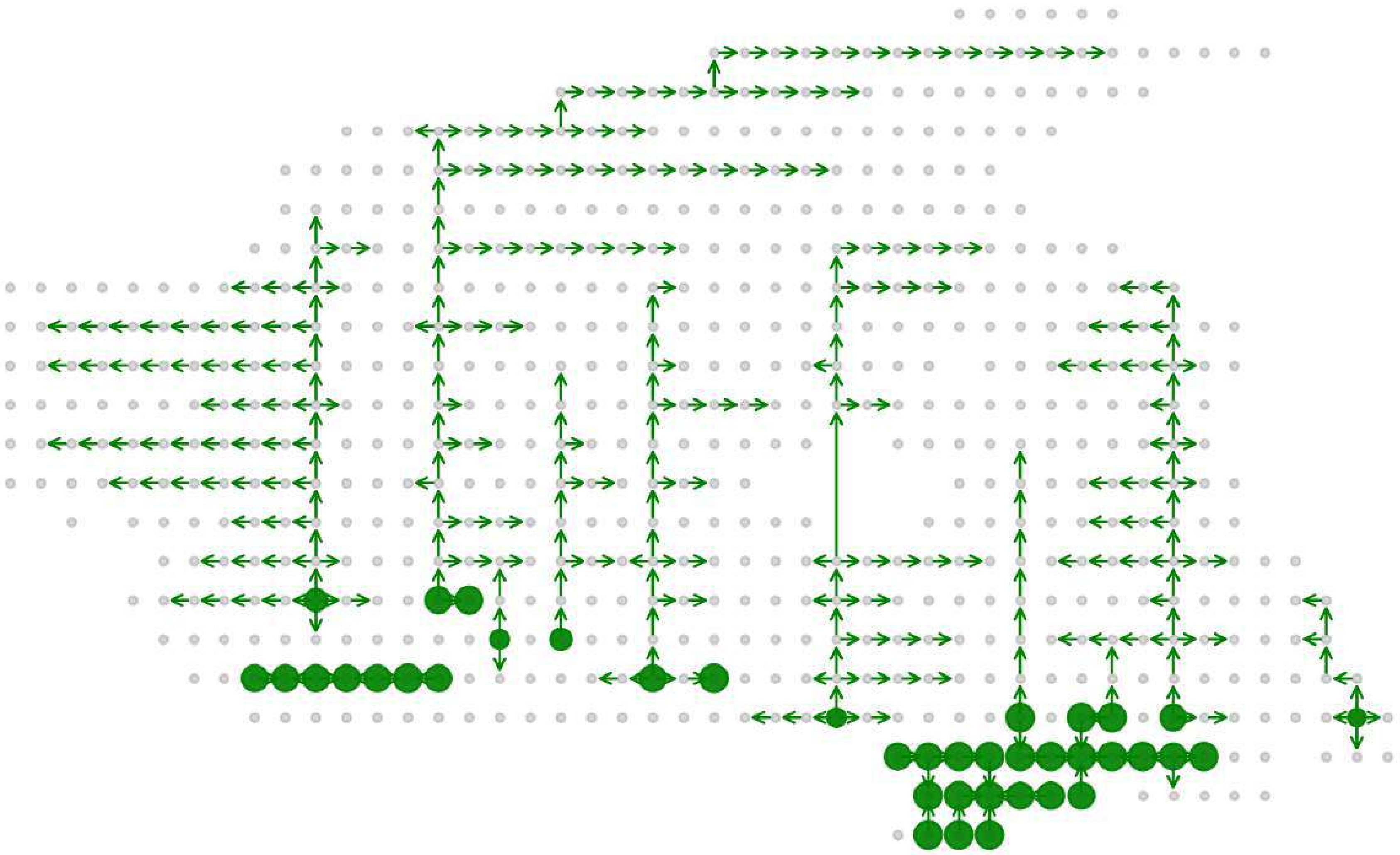
# Geospatial optimization with economies of scale

*Application: spatially-explicit infrastructure expansion*



Thiago Rodrigues



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# Uncertainty tools (Temoa)

## Monte Carlo

Samples distributions of input parameters.

Outputs distributions of outcomes.

## Method of Morris

Global sensitivity analysis.

Ranks sensitivity of input parameters.

## Modelling to Generate Alternatives (MGA)

Maximally-different near-optimal solutions.



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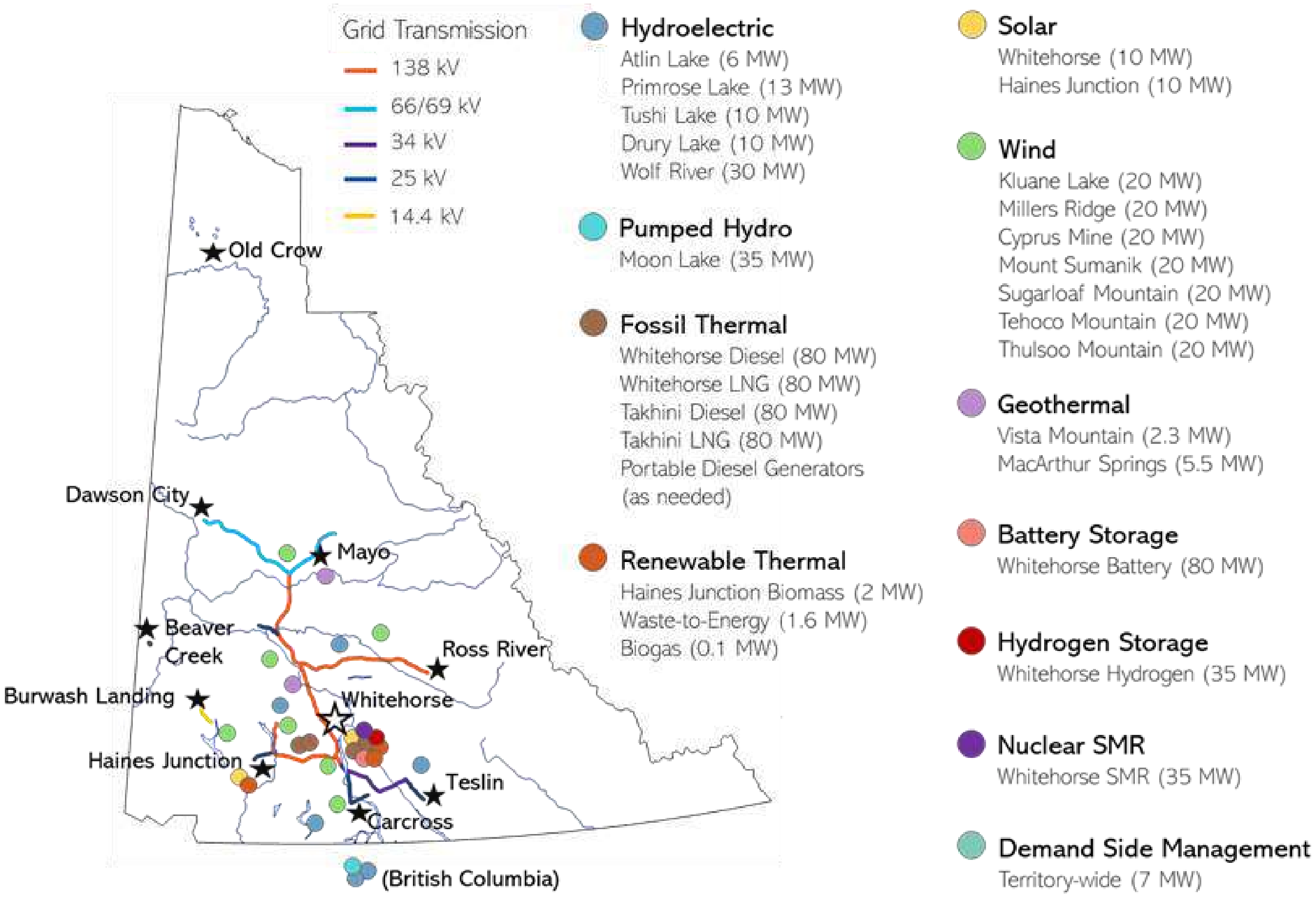
# Uncertainty applications

*Monte Carlo – Robust decision making for Yukon's power system*

Chris Fitzgibbon

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# Uncertainty applications

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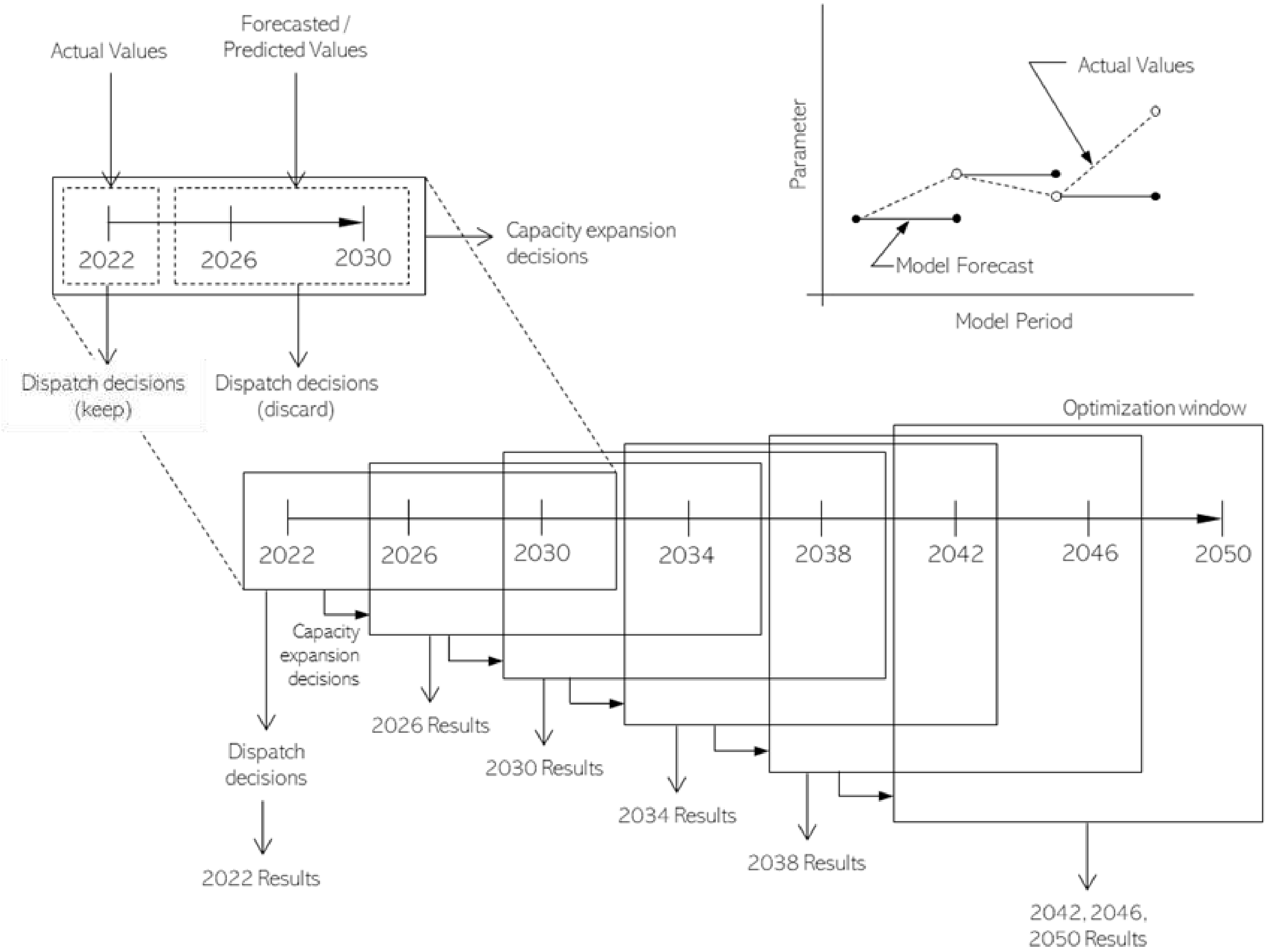




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# Uncertainty applications

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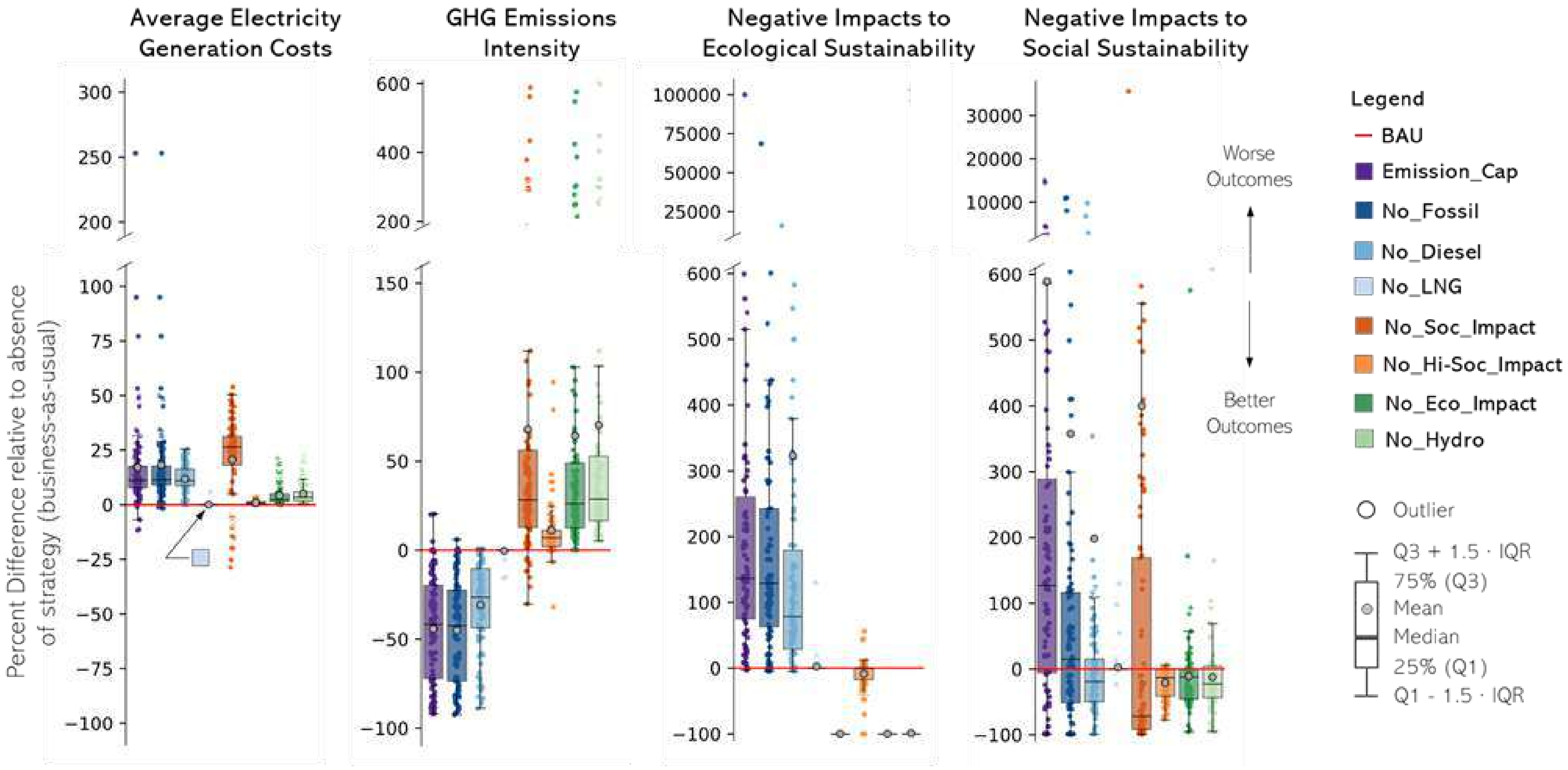


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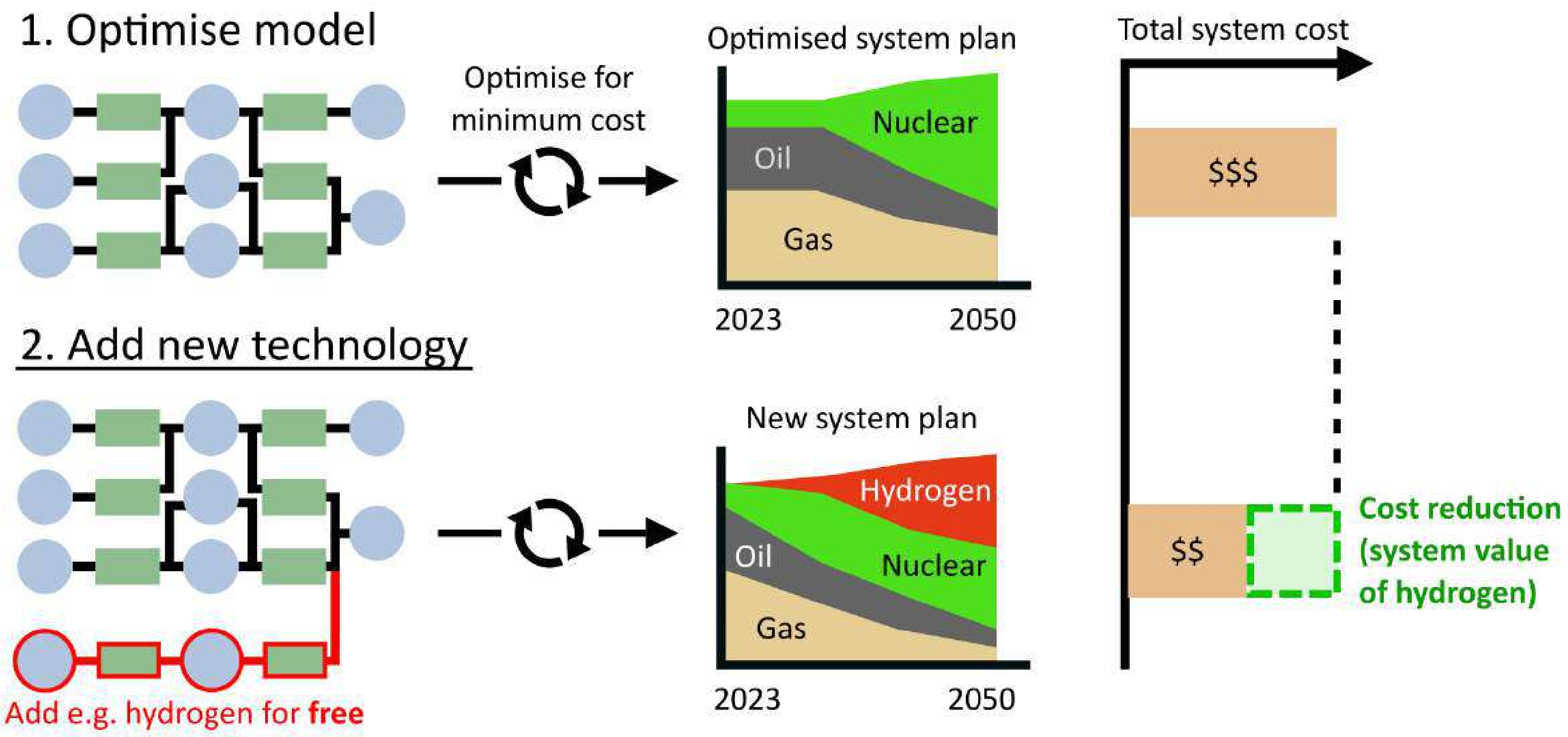
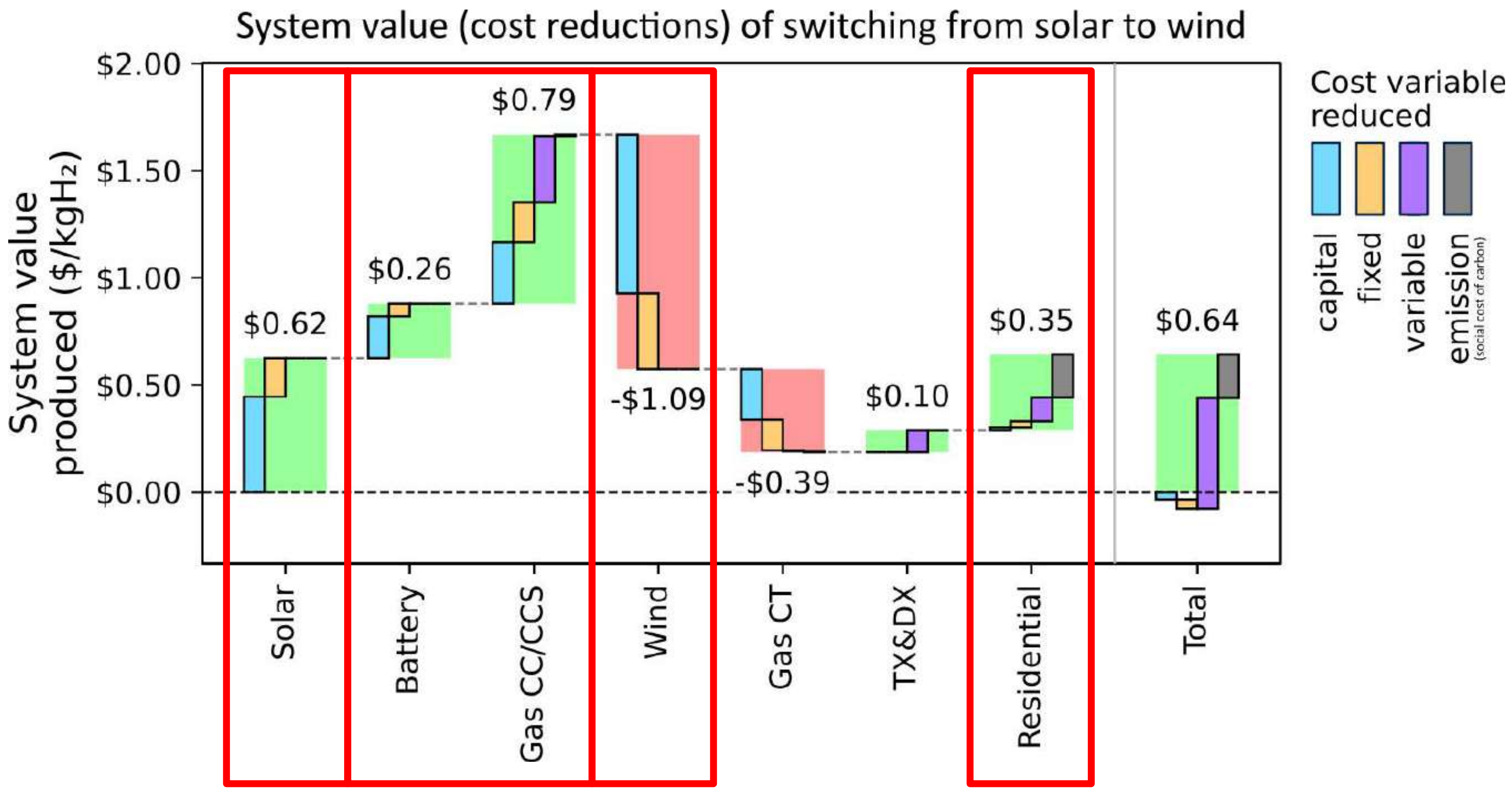
# System Value Assessment (SVA)

*Method*



# System Value Assessment (SVA)

*Pairing $H_2$ production with wind outperforms solar – boosted by multi-sector interactions*



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# The Canadian Open Energy Model (CANOE)

*Summary*

National-scale, multi-sectoral ESOM for Canada.

Open source and open access

Modular construction. Flexible scope and resolution.

Built for uncertainty analysis.

## Model features:

Embodied carbon

Endogenous material flows

EV charging

Oil refineries

Seasonal storage

Endogenous technological learning

Survival curves

Growth rate constraints

**More on CANOE**

**Our Temoa branch**

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