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# Exploring the Near-Optimal Solution Space of an Energy System Optimization Model

**Cameron Wade**, Peter Wild, Andrew Rowe

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# Outline

# Clean Energy Transitions are Difficult!

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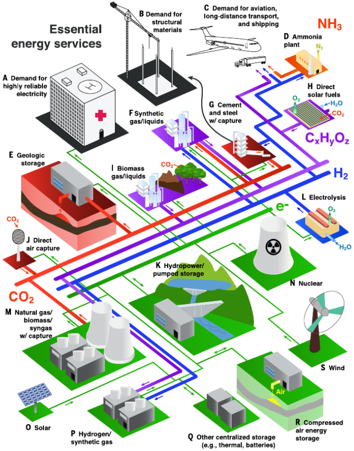
1. Net-zero compliant $\rightarrow$ energy system overhaul
2. Capital intensive, long-lived assets
3. (1) + (2) $\implies$ large investments under deep uncertainty

# Energy system (planning) models as decision support tools

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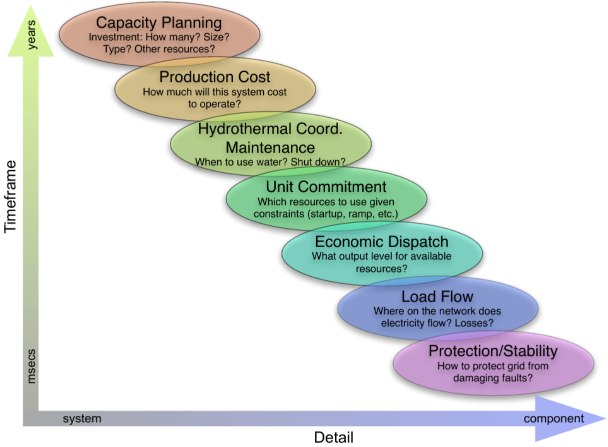


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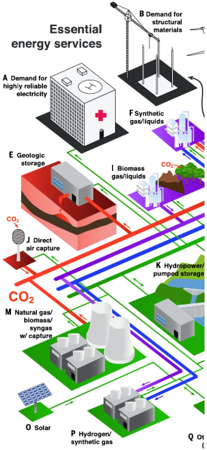
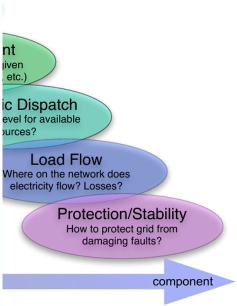
# Energy system (planning) models as decision support tools




Uncertainty

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# Uncertainty Modelling

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**Parametric Uncertainty**, e.g.:

- Future natural gas prices
- Future capital costs
- Future weather/climate
- etc...

**Structural Uncertainty**:

- Manifestations of mathematical abstractions
- Knife-edge solutions
- Penny switching
- ...

Methodologies:

- Stochastic optimization
- Monte Carlo
- Sensitivity Analyses
- Method of Morris
- ...

Methodologies:

- Modelling to Generate Alternatives (MGA)

# Modelling to Generate Alternatives

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- **A systematic methodology to navigate the near-optimal solution space (NOSS)**
- Select from NOSS solutions that are distinctive yet similar in cost
- **Intention**: *Not* a singular, 'optimal' answer. Instead a portfolio of alternative solutions that exhibit the degree of flexibility in the model solution.
- **Application**: Elucidate to energy system planning stakeholders the breadth of possible futures that exist w/ ∼negligible cost differences for a given scenario.

# Modelling to Generate Alternatives

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- In the abstract, applies to all optimization problems
- Introduced in 1982 in land-use planning
- First proposed for use in energy system planning in 2011 (DeCarolis, 2011)
- Recent uptick in applications (Lombardi et al., 2020; Neumann et al. 2021)
- No known application in Canadian context

# MODEL

# MGA Overview

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## Convex Optimization Problem in Standard Form

$$
\begin{aligned}
\underset{\vec{x}}{\text{minimize}} \quad & f(\vec{x}) \\
\text{subject to} \quad & g_i(\vec{x}) \leq 0 \\
& h_j(\vec{x}) = 0 \\
& \vec{x} \in \mathbb{R}^n
\end{aligned}
$$

# MGA Overview



**3 Step Process**

1. Solve original optimization problem.
2. Define NOSS by using optimal solution of (1) as an anchor point.
3. Define new objective function ('search direction') to select new, near-optimal solutions.
4. (Iterate (3) until satisfied)

# MGA Overview

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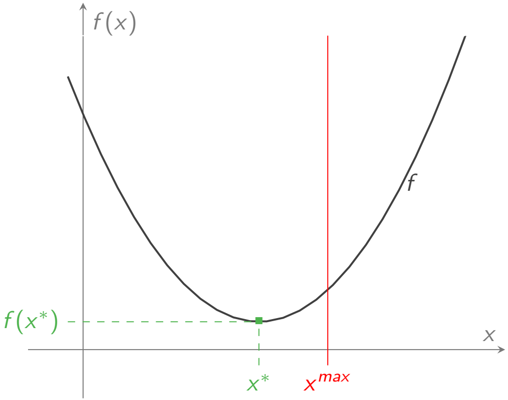
$$
\begin{aligned}
\underset{x}{\text{minimize}} \quad & f(x) \\
\text{subject to} \quad & x - x^{max} \leq 0 \\
& x \in \mathbb{R}
\end{aligned}
$$



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& x \in \mathbb{R}
\end{aligned}
$$

$$\downarrow$$

$$
\boxed{
\begin{aligned}
\underset{x}{\text{minimize}} \quad & m(x) \\
\text{subject to} \quad & x - x^{max} \leq 0 \\
& f(x) - (1+\epsilon)f(x^*) \leq 0 \\
& x \in \mathbb{R}
\end{aligned}
}
$$

# MGA Overview

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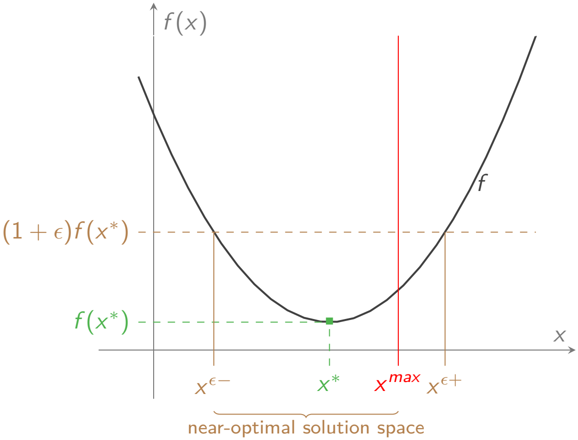

# Application



- Energy system planning model of BC & AB
- Electricity system and emissions impacts of electrification of BCs entire road transportation fleet by 2050.
- 2020 - 2050
- Fed Carbon Tax + Electrification Mandate

Based off the following studies:


- Keller, Victor, et al. "Electrification of road transportation with utility controlled charging: A case study for British Columbia with a 93% renewable electricity target." *Applied Energy* 253 (2019): 113536.
- Keller, Victor, et al. "Electricity system and emission impact of direct and indirect electrification of heavy-duty transportation." *Energy* 172 (2019): 740-751.

# System Representation

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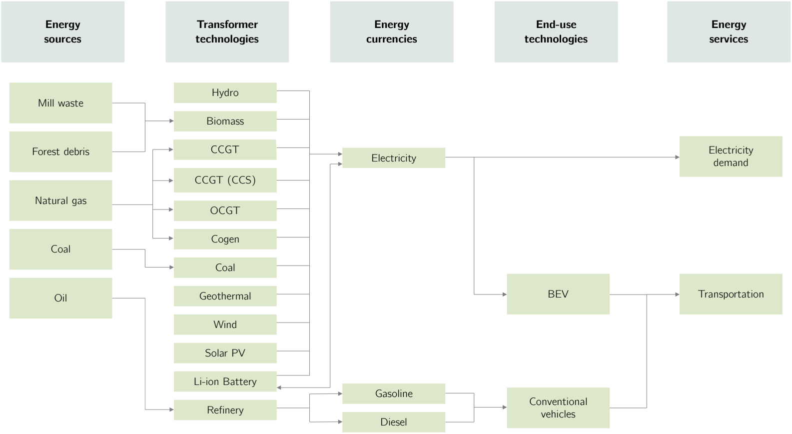

# MGA Application

**Objective: Find solutions that are similar in cost to optimal solution but differ in system composition and operation.**

Introduce slack variable $\epsilon$ to define near-optimal solution space"

- $\epsilon \in \{0.01, 0.02, 0.03, 0.04, 0.05, 0.075, 0.1\}$

Determine search direction:

- Minimize and maximize total 'activity' of the following (groups of) technologies:
  1. Wind
  2. Solar PV
  3. Battery
  4. CCGT & CCGT-CCS
  5. Transmission

# RESULTS

# Optimal Results

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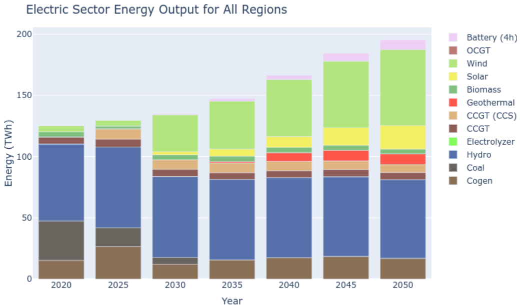


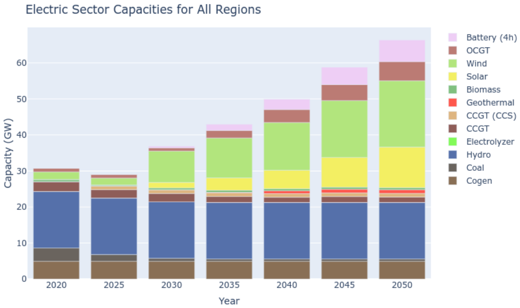


Annual capacities and generation for the Alberta and British Columbia electricity sectors for the years 2020-2050.

# Optimal Results (cont'd...)

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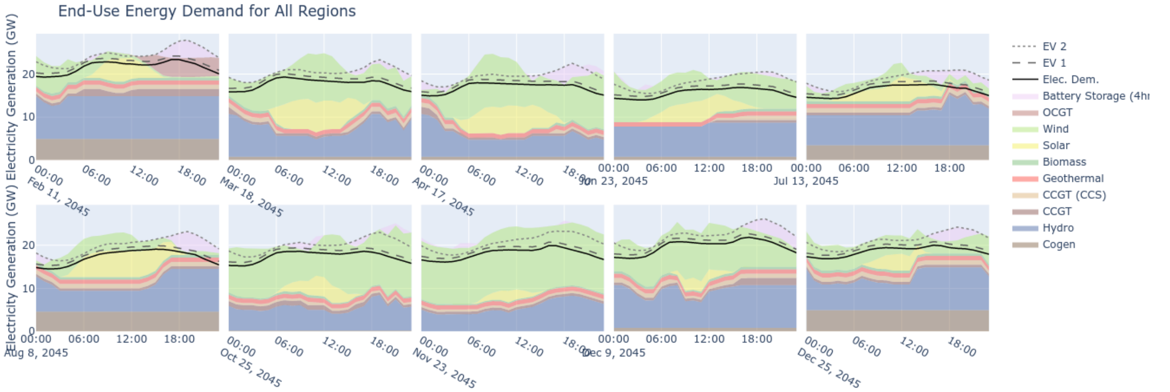


Hourly electricity generation for the 10 representative days in 2045.

# Alternatives....

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**What happens when we maximize total Solar PV activity at a 2% cost premium?**

# Alternatives....

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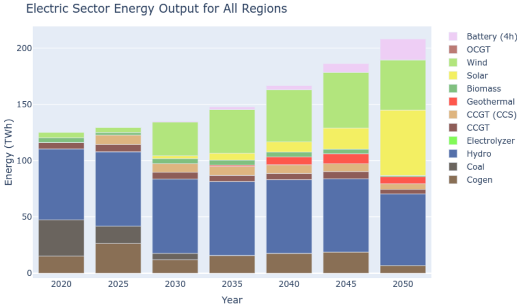
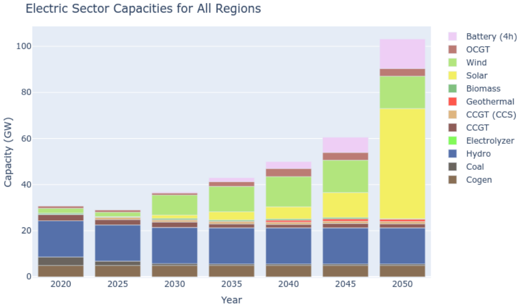



**(a)**




**(b)**

Annual capacities and generation for the Alberta and British Columbia electricity sectors for the years 2020-2025 under the MGA scenario of maximizing solar PV generation for $\epsilon = 0.02$

# Envelopes of the future system...

**From the 70 alternatives selected, can we get an idea of the possible futures for each technology?**

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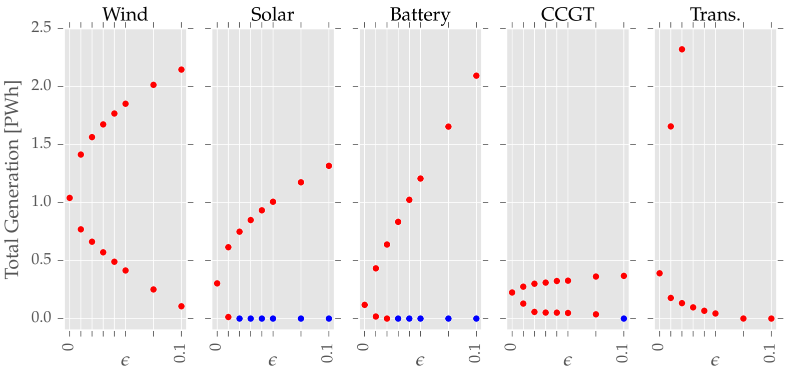


Near-optimal solution space for selected groups of technologies under different slack constraints.

# A set of possible futures...

What can possible futures look like under the same set of assumptions?

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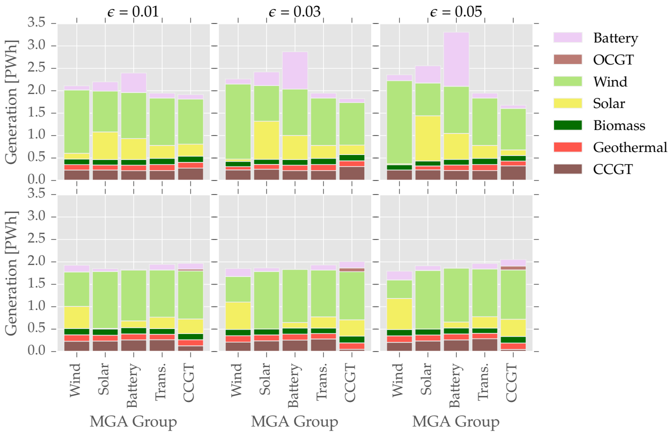


Breakdown of total generation as different technology groups are maximized (top row) and minimized (bottom row) with the MGA methodology.

# System level insights...

From the 70 alternatives, can we draw out any system-level insights related to technology development and activity?

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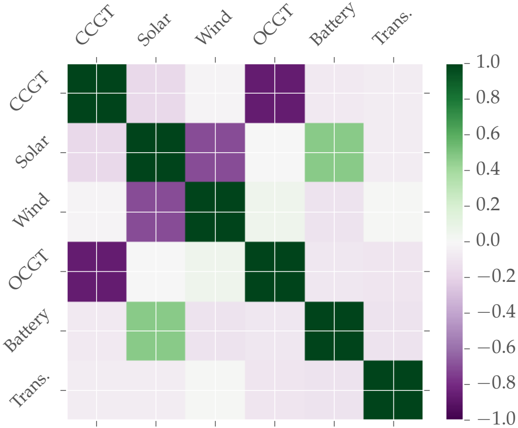
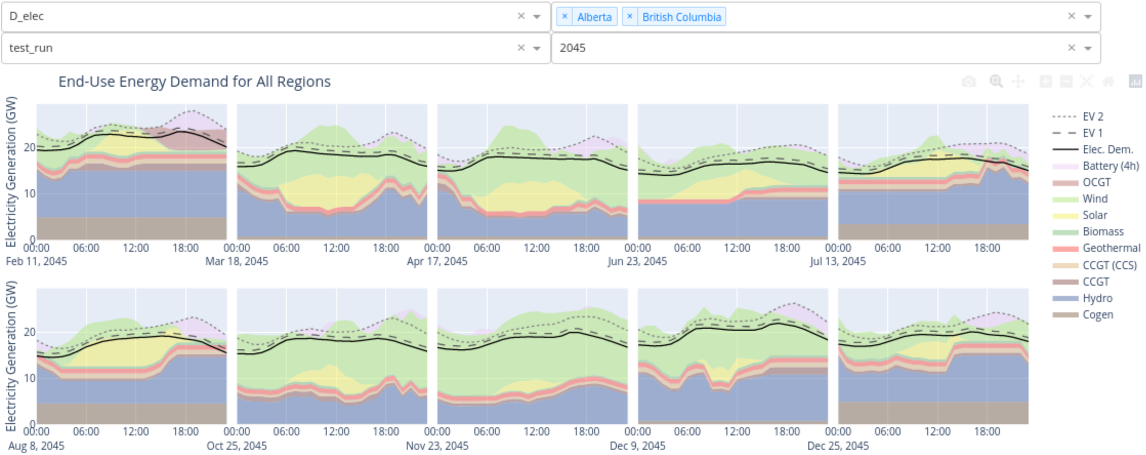



Correlation of total technology generation for all near-optimal solutions.

# Under development...






Screenshot of the current interactive dashboard to explore the suite of near-optimal solutions.

# Concluding thoughts

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- What policy gaps does MGA fill?
- Usability for policy design?
- Benefits from being integrated in a national modelling platform?

# Thank you!

Questions or Comments?

cameronwade@uvic.ca