The math of energy-economy models CIMS and CIMS-Urban

Exploring the math behind the models used by EMRG (SFU) to evaluate clean energy policy

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Outline

- What is an energy-economy model?
- What is CIMS and how is it used?
- How does CIMS work? (math!)
- How are the parameters estimated? (math!)
- Why did we develop CIMS-Urban?
- How does CIMS-Urban work?
- How are the parameters estimated? (current research)

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What is an energy-economy model?

- A computer model designed to capture some subset of the determinants of *energy* consumption within an *economy*
- Energy consumption is linked to GHG emissions and local air pollution
- Currently, these models tend to be used to evaluate public policies to reduce emissions

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Qualities of an energy-economy model

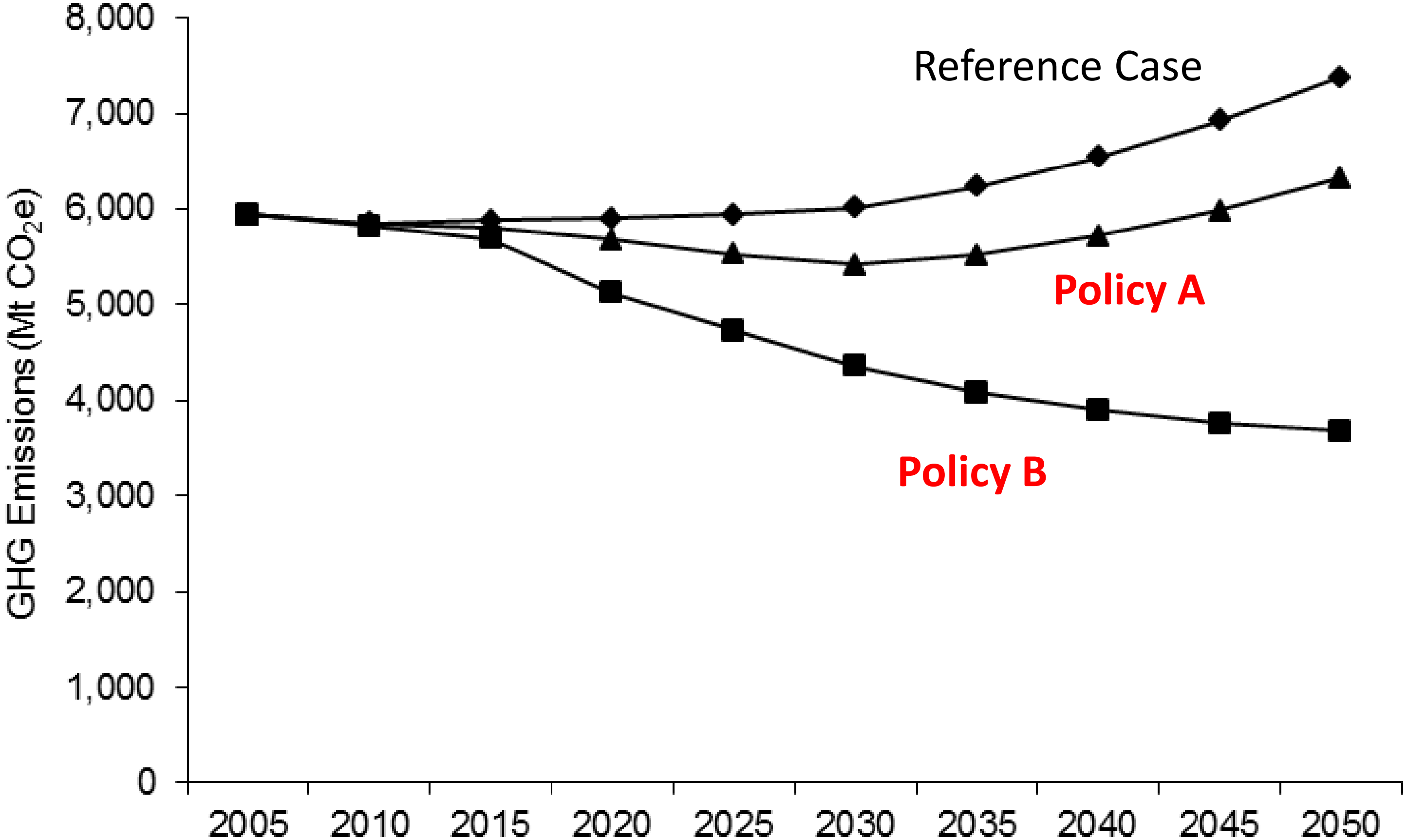
- Degree of technological explicitness: Does the model explicitly represent the technologies that produce, consume, and transport energy or does it operate at a more aggregate level?
- Degree of preference incorporation: Does the model take into account human preferences or are decisions based only on “cost minimization”?
- Degree of equilibrium feedbacks: Are the indirect effects of a change captured?

➢ Inherent trade-offs among these qualities

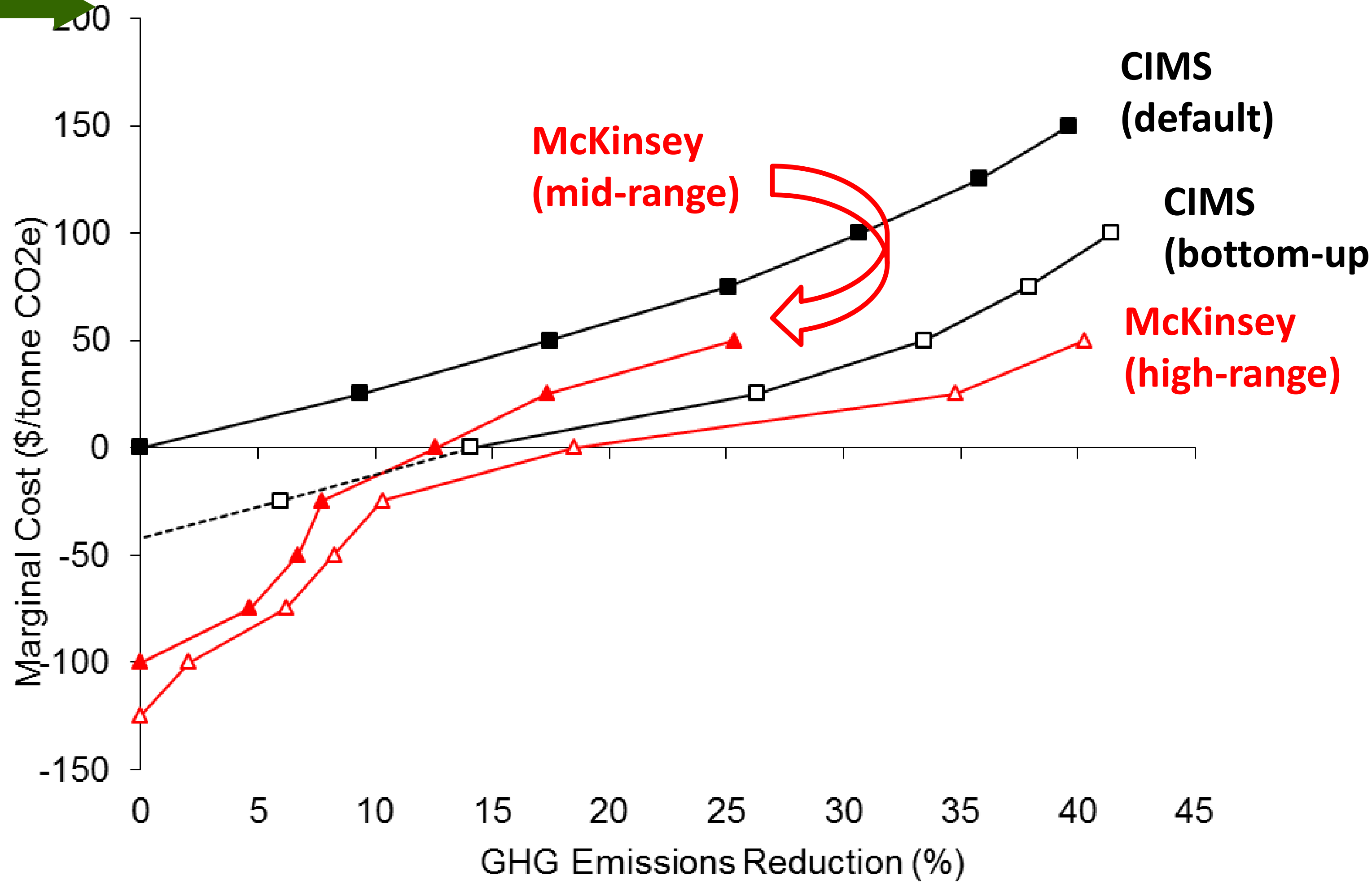
Characterizing CIMS in terms of these qualities

- Technological explicitness: To a significant degree
- Preference incorporation: To a significant degree
- Equilibrium feedbacks: To some degree

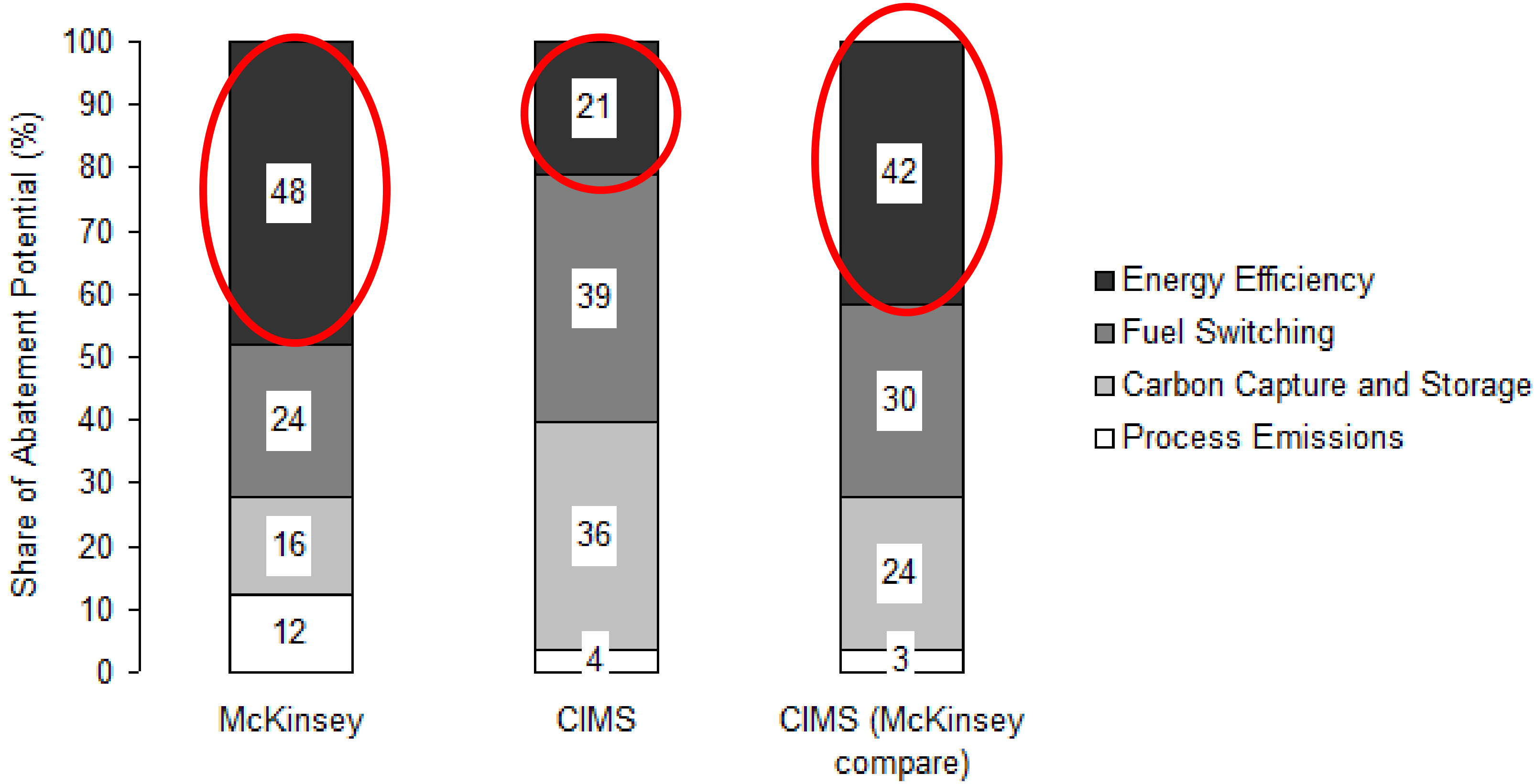
Economy-wide GHG emissions (combustion only)



GHG abatement cost curves, 2030



Contributions to GHG emissions abatement at $50/tonne CO_2e



CIMS technology choice algorithm

Market share
(new capital stock)
technology j

$$MS_j = \frac{\left[CC_j * \frac{r}{1-(1+r)^{-n_j}} + MC_j + EC_j + i_j\right]^{-v}}{\sum_{k=1}^{K}\left\{\left[CC_k * \frac{r}{1-(1+r)^{-n_k}} + MC_k + EC_k + i_k\right]^{-v}\right\}}$$

"Technology" can be infrastructure, buildings, industrial plants and equipment, electricity generation and other energy supply equipment, vehicles and other transport equipment, and appliances and other household durable goods

Life cycle cost

Life cycle cost technology j (/year)

$$LCC_j = CC_j * \frac{r}{1-(1+r)^{-n_j}} + MC_j + EC_j$$

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Life cycle cost

$$LCC_j = CC_j * \frac{r}{1-(1+r)^{-n_j}} + MC_j + EC_j$$

Life cycle cost technology j (/year)

Capital cost j

Maintenance & operation cost j (/year)

Energy cost j (/year)

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Life cycle cost

Life cycle cost technology j (/year)

Capital cost j

Discount rate

Maintenance & operation cost j (/year)

Energy cost j (/year)

$$LCC_j = CC_j * \frac{r}{1-(1+r)^{-n_j}} + MC_j + EC_j$$

Life span j

Capital recovery factor (converts one-time capital cost to /year)

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CIMS technology choice algorithm

Market share (new capital stock) technology j

$$MS_j = \frac{\left[CC_j * \frac{r}{1-(1+r)^{-n_j}} + MC_j + EC_j + i_j\right]^{-v}}{\sum_{k=1}^{K}\left\{\left[CC_k * \frac{r}{1-(1+r)^{-n_k}} + MC_k + EC_k + i_k\right]^{-v}\right\}}$$

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CIMS technology choice algorithm

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Life cycle cost technology j (/year)

Summation across all other technologies K available to provide the energy service

Life cycle cost technology k (/year)

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CIMS behavioral parameters

$$MS_j = \frac{\left[CC_j * \frac{r}{1-(1+r)^{-n_j}} + MC_j + EC_j + i_j\right]^{-v}}{\sum_{k=1}^{K} \left\{\left[CC_k * \frac{r}{1-(1+r)^{-n_k}} + MC_k + EC_k + i_k\right]^{-v}\right\}}$$

Discount rate (time preference)

Intangible cost technology j

Heterogeneity

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CIMS behavioral parameters

$$MS_j =$$

Discount rate
(time preference)

$$\frac{\left[CC_j * \frac{r}{1-(1+r)^{-n_j}} + MC_j + EC_j + i_j\right]^{-v}}{\sum_{k=1}^{K}\left\{\left[CC_k * \frac{r}{1-(1+r)^{-n_k}} + MC_k + EC_k + i_k\right]^{-v}\right\}}$$

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Discount rate

- The rate at which we "discount" the future relative to the present
- Why do we do this?
  - Humans are impatient (uncertainty)
  - Returns to alternative investments
  - Optimism about the future
- Humans apply different rates in different situations
- What rates should be used inside a model?
- Intergenerational discounting

CIMS behavioral parameters

$$MS_j = \frac{[CC_j * \frac{r}{1-(1+r)^{-n_j}} + MC_j + EC_j + i_j]^{-v}}{\sum_{k=1}^{K}\left\{[CC_k * \frac{r}{1-(1+r)^{-n_k}} + MC_k + EC_k + i_k]^{-v}\right\}}$$

Intangible cost technology j

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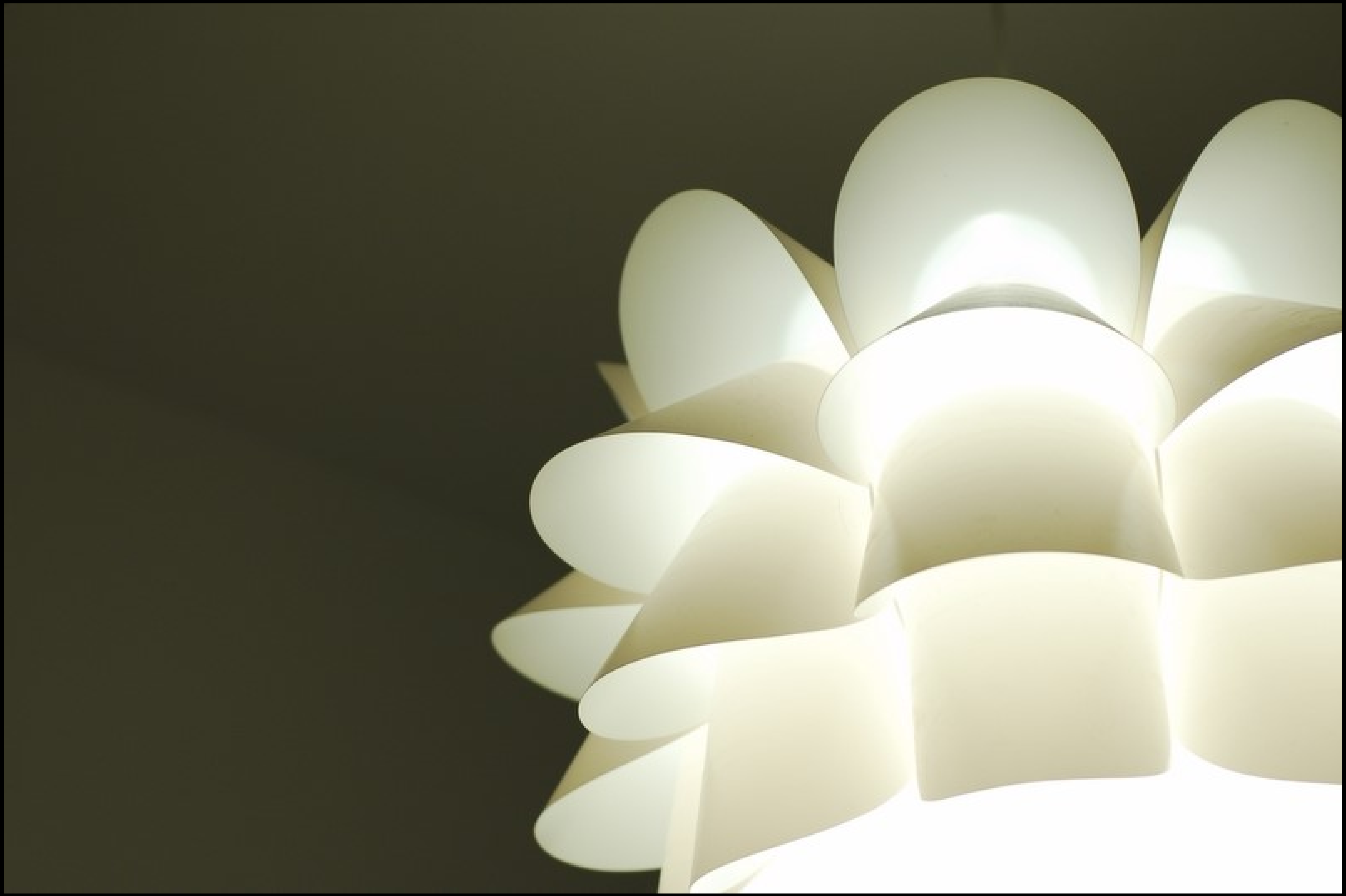

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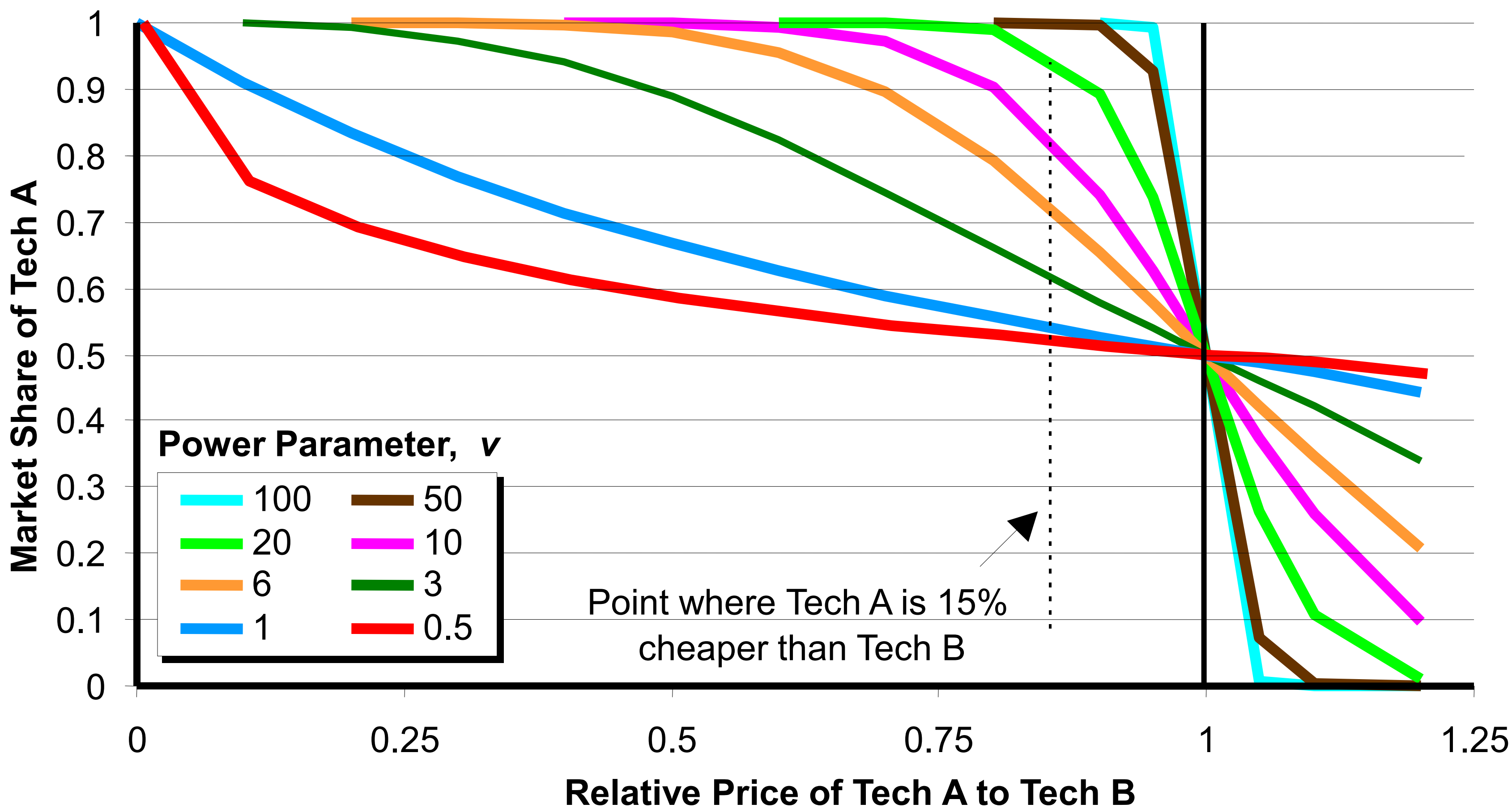
CIMS behavioral parameters

$$MS_j = \frac{\left[CC_j * \frac{r}{1-(1+r)^{-n_j}} + MC_j + EC_j + i_j\right]^{-v}}{\sum_{k=1}^{K}\left\{\left[CC_k * \frac{r}{1-(1+r)^{-n_k}} + MC_k + EC_k + i_k\right]^{-v}\right\}}$$

Heterogeneity

Inverse power function



Source: Nyboer, 1997

Where do behavioral parameter values come from?

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- Revealed preference (RP) data (preferences as revealed by historical choices)
  - Drawback: results may not be applicable to new technologies and circumstances that deviate from historical record

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- Revealed preference (RP) data (preferences as revealed by historical choices)
  - Drawback: results may not be applicable to new technologies and circumstances that deviate from historical record
- **Stated preference (SP) data (preferences as revealed by survey responses)**
  - Drawback: hypothetical responses are not the same as actual choices

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Use of SP data to estimate CIMS behavioral parameters

- Conduct surveys that present participants with hypothetical choices between technologies
- Use the response data to estimate multi-nomial logit (MNL) models – an MNL model is a type of discrete choice model
- Translate the resulting models into CIMS parameters

Axsen et al., 2009 (stated and revealed, neighbor effect for hybrid-electric vehicles); **Horne et al., 2005 (personal transportation decisions)**; Jaccard and Dennis, 2006 (home energy decisions); Rivers and Jaccard, 2005 (industrial steam generation technology decision); Washbrook et al., 2006 (impact of specific policies on commuter mode choice)

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General form of an MNL model

Utility of alternative j (used to calculate its market share)

$$U_j = \vec{\beta}_j \times \vec{X}_j + ASC_j$$

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Vector of attribute values for alternative j

General form of an MNL model

Vector of weighting coefficients for each of alternative j's attributes

Utility of alternative j (used to calculate its market share)

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Vector of attribute values for alternative j

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General form of an MNL model

$$U_j = \vec{\beta}_j \times \vec{X}_j + ASC_j$$

- U_j: Utility of alternative j (used to calculate its market share)
- $\vec{\beta}_j$: Vector of weighting coefficients for each of alternative j's attributes
- $\vec{X}_j$: Vector of attribute values for alternative j
- ASC_j: Constant contributing to j's utility (Alternative-specific Constant)

Specific example of an MNL model (Horne et al., 2005)

- Investigated personal transportation decisions
- Presented 1150 people with eight hypothetical choices each
  - Four choices with respect to vehicle type (energy source)
  - Four choices w.r.t. mode for commuting (drive alone, carpool, public transit, park and ride, walk or cycle)

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Utility for each vehicle type

Capital cost

Fuel cost

Fuel availability

$$U = \beta_{CC} \times CC + \beta_{FC} \times FC + \beta_{FA} \times FA + \beta_{EXP} \times EXP + \beta_{POW} \times POW + ASC$$

Express lane access

Power

Attributes selected based on literature review and policy relevance

Translating into CIMS:

Translating into CIMS: *r* parameter

- As demonstrated by Train (1985), the discount rate can be obtained from an MNL model as follows:

MNL capital cost coefficient

Life span of the technology

$$r = \frac{\beta_{CC}}{\beta_{OC}} \times (1 - (1 + r)^{-n})$$

MNL operating cost coefficient

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Translating into CIMS: *i* parameter

- Monetize each non-financial contribution to utility, $\beta_m * X_m$ as an annual cost, then sum across all the non-financial attributes M:

$$i_j = \sum^{M} \left(\frac{\beta_m}{\beta_{OC}} \right) \times X_m$$

Intangible cost technology j

Value for non-financial attribute m

- Ability not only to simulate human behavior for a given set of attribute values, but also to investigate the impact of a change to a specific non-financial attribute value (or values)!

Translating into CIMS: *v* parameter

- Set the market share formula for the MNL model (K competing technologies) …

Utility of technology j

$$MS_j = \frac{e^{U_j}}{\sum_{k=1}^{K} e^{U_k}}$$

- … equal to the CIMS market share formula …

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CIMS technology choice algorithm

Market share (new capital stock) technology j

$$MS_j =$$

Life cycle cost technology j (/year)

$$\frac{\left[CC_j * \frac{r}{1-(1+r)^{-n_j}} + MC_j + EC_j + i_j\right]^{-v}}{\sum_{k=1}^{K}\left\{\left[CC_k * \frac{r}{1-(1+r)^{-n_k}} + MC_k + EC_k + i_k\right]^{-v}\right\}}$$

Summation across all other technologies K available to provide the energy service

Life cycle cost technology k (/year)

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Translating into CIMS: *v* parameter

- Set the market share formula for the MNL model (K competing technologies) …

Utility of technology j

$$MS_j = \frac{e^{U_j}}{\sum_{k=1}^{K} e^{U_k}}$$

- … equal to the CIMS market share formula …
- … and solve for *v*
- The two sides of this relationship are not identical in form; however performance is similar (Horne et al., 2005)
- No analytical solution; therefore, Horne et al. (2005) programmed a solver routine to minimize error between the two sides

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A new direction: city-level modeling

A new direction: city-level modeling

"For decades, federal governments and international bodies have been incapable of adequately tackling the problem. Now, however, the world's cities have taken the lead in fighting the impacts of climate change locally, and their collective efforts are having a global impact."

Bloomberg Philanthropies, 2017. Sustainable cities. https://www.bloomberg.org/program/environment/sustainable-cities/

Qualities of an energy-economy model

- Degree of technological explicitness
- Degree of preference incorporation
- Degree to which equilibrium feedbacks are captured

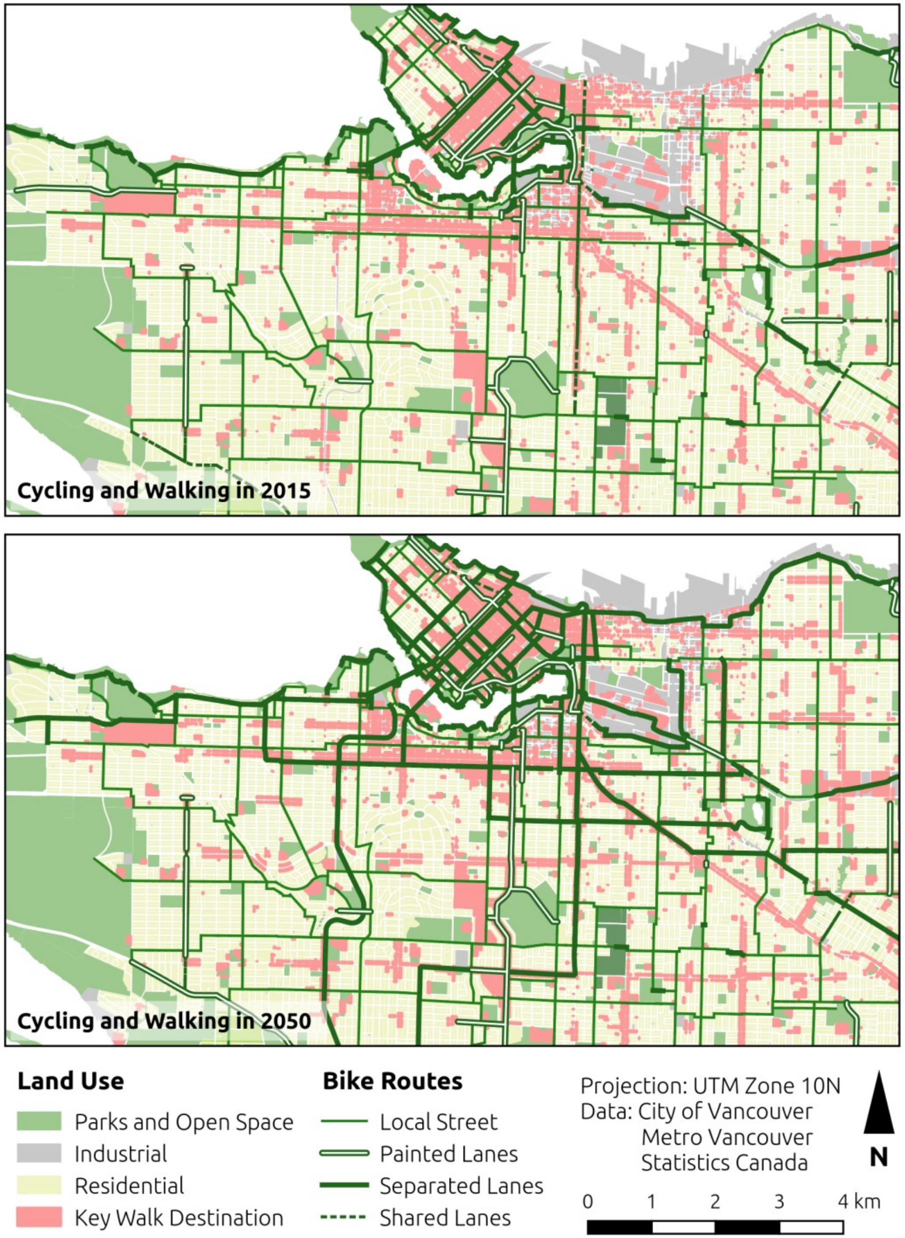
➢ There are inherent trade-offs among these qualities

Qualities of an energy-economy model

- Degree of technological explicitness
- **Degree of spatial explicitness**
- Degree of preference incorporation
- Degree to which equilibrium feedbacks are captured

Physical resolution (annotation bracketing the first two items)

➢ There are inherent trade-offs among these qualities



A new model: CIMS-Urban

CIMS energy-economy model + GIS-based land-use and infrastructure model

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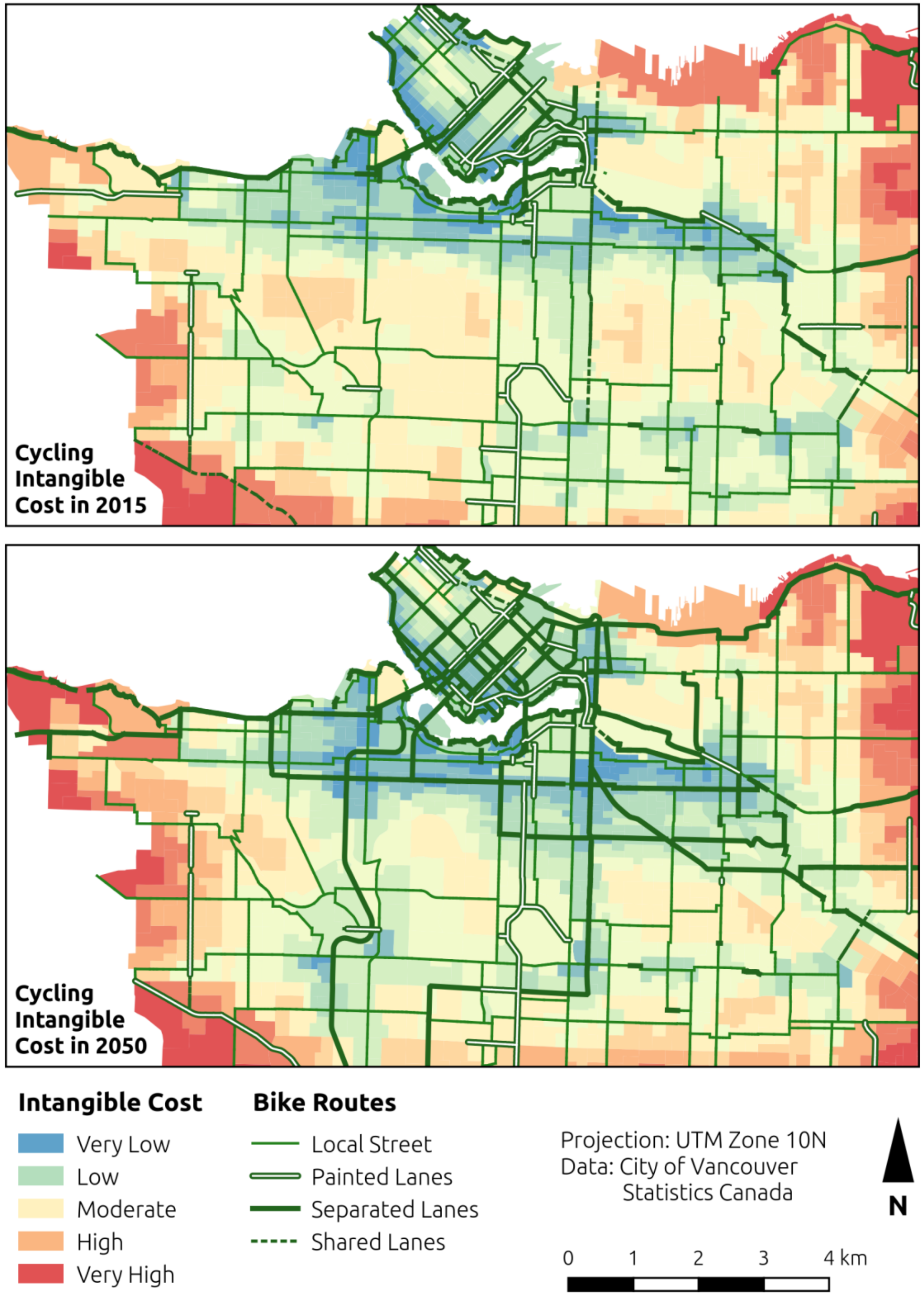
A key action: mode switching

- An intended result of a number of municipal policies
- CIMS-Urban evaluates transportation "network quality" for each mode at the level of the Dissemination Area (Statistics Canada)
- Uses these estimates of network quality to derive the intangible cost parameter in CIMS for that mode


Cycling Intangible Cost in 2015
Cycling Intangible Cost in 2050
Intangible Cost
Very Low
Low
Moderate
High
Very High
Bike Routes
Local Street
Painted Lanes
Separated Lanes
Shared Lanes
Projection: UTM Zone 10N
Data: City of Vancouver
Statistics Canada
N
0
1
2
3
4 km

Renewed interest in stated preference research

- Current version of CIMS-Urban is based on revealed preference data
- Our existing stated preference research is insufficient for setting behavioral parameters in the spatial model
- For example, to estimate the intangible costs of cycling throughout a city in CIMS-Urban, need to take into account distance to destination, gradient of path, quality of path, etc.
- Preparing to conduct more stated preference surveys over the next year