How higher spatial resolution impacts energy systems analysis: Evidence from multi-region TIMES-Ireland model

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Acknowledgement

A review of spatial resolution and regionalisation in national-scale energy systems optimisation models

Vahid Aryanpur, Brian O’Gallachoir, Hancheng Dai, Wenyong Chen, James Gynn

Further details:

GitHub: https://github.com/MaREI-EPMG/times-ireland-model
Zenodo: https://zenodo.org/record/5517363

TIM: Modelling pathways to meet Ireland’s long-term energy system challenges with the TIMES-Ireland Model (v1.0)

Olexandr Balyk, James Gynn, Vahid Aryanpur, Ankita Gaur, Jason McGuire, Andrew Smith, Xiuteng Yue, and Hannah Daly

Decarbonisation of passenger light-duty vehicles using spatially resolved TIMES-Ireland Model

Vahid Aryanpur, Olexandr Balyk, Hannah Daly, Brian Ó Gallachóir, James Gynn

Results: https://tim-carbon-budgets-2021.netlify.app/results
Background and scope

Background:

- **Problem:** Energy systems models are usually **criticised** for the aggregate treatment of spatial dynamics.

- **Solution:** Sub-national details should be incorporated into the national energy system analysis.

Outlines:

I. Reviewing existing national-scale ESOMs
II. Evidence from multi-region TIMES-Ireland Model
III. Lessons learnt from review
IV. Lessons learnt from TIM
Motivations for higher spatial resolution

Socio-economic, environmental & political motivations
- Demographics, Regional responsibilities, Political acceptability
- Local actors, stakeholders, Income level

Supply-side motivations
- VRE generation potential
- Infrastructure development
- Regional resource endowment

Demand-side motivations
- Regional demand variability
- Regional consumer preferences
- Impact of climate condition on demand

Legend
Stylised
Complete
Systematic review

- 1024 publications
- 76 national-scale
- 36 models
- 22 countries

Filtration process: National-scale multi-region ESOM

Sectoral focus

- Power sector 42%
- Energy system 33%
- Buildings 14%
- Others 11%

Ireland’s Climate Action Plan (CAP)

- Transport is the largest energy-consuming sector in Ireland (>40%)
- This sector significantly relies on fossil fuels (~40% of energy-related CO₂ emissions)
- **Private cars** are responsible for the largest share of transport emissions at 40%
- **CAP**: a 51% reduction in GHG emissions by 2030 and carbon-neutral society by 2050

**CO₂ emissions by transport & the targets**

- 2030 target: 51% reduction
- 2050 target: Carbon-neutral

**Supporting EV adoption by monetary incentives**

<table>
<thead>
<tr>
<th>Year</th>
<th>Emissions (Million ton CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>~40k</td>
</tr>
<tr>
<td>2030</td>
<td>840k</td>
</tr>
</tbody>
</table>
Supply-side Modules

**Resources and Potentials**
- Fossil fuel: Oil, Gas, Coal
- Renewable: Wind, Hydro, Solar, Biomass

**Power**
- Fossil-Fired
- Biogas-Fired
- CCS (Gas/Biomass)
- Renewable

**Fuel Supply**
- Oil products
- NG/Biogas
- Liq. Biofuels
- Hydrogen

**Imports**
- Electricity
- Oil products
- Biofuels
- Natural gas

Demand-side Modules

**End-use Technologies**

**Energy Service Demands**
- Residential & Service
  - Space heating
  - Hot water
  - Electricity
  - Others
- Industrial
  - Chemicals
  - Machinery
  - Metals
  - Food & beverage
  - Others

**Carbon Constraint (kt CO₂)**

**Transport Module (multi-region)**

**Passenger (pkm):**
- Active modes (Walk, Cycle)
- 2-Wheelers
- Light-Duty Vehicles (Car, Taxi)
- Heavy-Duty Vehicles (Bus, Train)

**Freight (tkm):**
- Light, Medium & Heavy Goods Trucks
- Others (PJ): Tourism, Navigation, Aviation

**Consumer Groups (Hurdle rates):**
- Low-income
- Medium-income
- High-income

**Scenario assumptions**
- Reference Scenario
- Alternative Scenarios

**Decarbonisation Measures**
- Monetary incentives
- Carbon tax
- Biofuel obligation
- Modal shift
- Occupancy rate

Transport sector structure within TIM

Region-specific parameters
- Vehicle fleet
- Infrastructure
- Demand
- Fuel economy
- Milage
- Population

Hurdle rates

Fuel supply modules (Power, H2 production, Refineries, Biorefineries, T&D, Trades)
- Gasoline
- Diesel
- CNG
- Biofuels
- LNG
- Electricity
- Hydrogen

Inland Freight
- Light Goods Trucks
  - ICEs, HEVs
  - FCVs
  - PHEVs, BEVS
- Medium & Heavy Goods Trucks
  - ICEs & HEVs
  - FCVs
  - BEVs
- Trains
  - ICEs, HEVs

Inland Passenger
- Active modes
  - Walk
  - Bike
- Light-Duty Vehicles
  - Cars & Taxis
    - ICEs & HEVs
    - FCVs
    - BEVs, PHEVs
  - 2-Wheelers
    - ICEs, BEVs
- Heavy-Duty Vehicles
  - Trains
    - ICEs (Train)
    - BEVs (Light rail)
    - BEVs (Train)
  - Buses
    - ICEs
    - FCVs
    - BEVs

Transport Demand
- Freight (tkm)
- Passenger (pkm)
- Others (PJ)

Short-range (below 5km)
Medium-range (5-30km)
Longe-range (Over 30km)

Tourism
Navigation
International Aviation
Domestic Aviation
Unspecified

Carlow
Dublin
Kildare
Kilkenny
Laois
Longford
Louth
Meath
Offaly
Westmeath
Wexford
Wicklow
Clare
Cork
Kerry
Limerick
Tipperary
Waterford
Galway
Leitrim
Mayo
Roscommon
Sligo
Cavan
Donegal
Monaghan

Hurdle rates
Retirement profile for existing and new cars

Diesel ICEs
Gasoline ICEs

Probaility of survival

County 1
County 2
County 26
County 2

Probaility of survival

PMs
VOC
NH3
SO2
NOx

CO2
CH4
N2O
Vehicle Purchase Decision

- **Hurdle rates** are used to capture the consumer behaviour when purchasing a transport technology.

![Average annual income map](image)

The map shows the distribution of average annual income across different regions in Ireland, with a gradient scale ranging from €32k to €66k. The bar chart to the right illustrates the frequencies of different income classes: high-income group (5-9%), medium-income group (17-27%), and low-income group (>39%).
<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Measures</th>
<th>LDV improvements</th>
<th>Carbon tax</th>
<th>BOS</th>
<th>Radical BOS</th>
<th>Active modes</th>
<th>OR 10% to 70%</th>
<th>MIR2021 to MIR2029</th>
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<tbody>
<tr>
<td>REF</td>
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<td>✓</td>
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<tr>
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</tbody>
</table>

REF: reference case without any measures  
BOS: Biofuel Obligation Scheme  
OR: Occupancy Rate  
MIR: Monetary Incentive Removal
Key Results:

- Individual measures cannot significantly reduce the emissions
- Shift strategy including fuel switching to biofuels and modal shift can cut CO₂ emissions up to 14%
- Improve, shift and carbon tax can together contribute to 31% of total reduction

Key point:
- Running scenarios without monetary incentives
- EV adoption is ~330k
Results: EV adoption

- The early removal may result in significant gap between the target and the probable penetration of EVs.

- Monetary incentives, applied individually, are unlikely to achieve the national decarbonisation targets.
### Spatially resolved distribution of EVs

<table>
<thead>
<tr>
<th>REF Scenario</th>
<th>MIR 2024 Scenario</th>
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<tbody>
<tr>
<td><strong>Number of EVs</strong></td>
<td><strong>EVs per capita</strong></td>
</tr>
<tr>
<td>Thousand EVs</td>
<td>EVs per capita</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------</td>
</tr>
<tr>
<td>71</td>
<td>0.10</td>
</tr>
<tr>
<td>175</td>
<td>0.22</td>
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</table>

*Images show the distribution of EVs across different scenarios.*
The averaging process hides the tendency of high-income consumers to purchase EVs.

Average retirement profile is another potential source of divergence.

Higher spatial resolution offers more reliable results for infrastructure development.

Higher spatial resolution can better inform policy makers.
Sensitivity analysis

Variations in hurdle rate

±5%: Insensitive
±25%: Almost symmetric
±50%: Unequally change

Lessons from +50% case
Different consumer preferences (non-monetary attributes) could significantly decelerate the EV growth

Lessons from -50% case
Encourage high & medium-income regions to buy EVs. This may increase regional disparities and equity issues.

Model dimension and solution time

- **Model detail:** >60 Attributes; >150 User Constraints; >300 Commodities; >2000 Technologies
- **Time slices:** 40
- **Planning Horizon:** 2018-2050
- **Number of periods:** 19
- **Computer Spec.:** 16 GB of RAM, Intel® Core™ i7-8705G at 3.1 GHz, 4 Cores

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Unit</th>
<th>Single-region (national level)</th>
<th>Multi-region* (26 counties)</th>
</tr>
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<tbody>
<tr>
<td>Number of equations</td>
<td>million</td>
<td>1.2</td>
<td>2.4</td>
</tr>
<tr>
<td>Number of variables</td>
<td>million</td>
<td>1.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Non-zero elements</td>
<td>million</td>
<td>5.9</td>
<td>11.3</td>
</tr>
<tr>
<td>Solution time</td>
<td>min</td>
<td>4.5</td>
<td>9.1</td>
</tr>
<tr>
<td>Iterations</td>
<td>number</td>
<td>94</td>
<td>169</td>
</tr>
</tbody>
</table>

* Just transport sector, others are nationally analysed.
Lessons learned from review

Impacts of higher spatial resolution on modelling results

Q1: When?

- Heterogeneous regions (weather-driven variability/energy demands) require more disaggregation
- Homogeneous areas, aggregated modelling is more efficient (reduce data/computational complexity)

Q2: How impact on development of VRES?

- Multi-region: Locations with higher availability $\xrightarrow{+} VRES$
- Single-region: Blind to grid bottlenecks and ignore congestion $\xrightarrow{+} VRES$
- Single-region: Average resource supply curve reduce the competitiveness $\xrightarrow{-} VRES$
- The trade-off should be analysed case-by-case

Q3: How impact on overall system costs?

- Disaggregation of renewable resources leads to lower costs
- Disaggregation of transmission grids leads to higher costs
Insights for modellers

- **Tractability**: Computational time and burden are manageable with a normal PC
- **Flexibility**: Easily switch between single and multi-region option
- **Transparency**: Code and data are publicly available, stakeholder engagement
- **Sensitivity**: Conduct ample scenarios & stress test to understand parametric and structural uncertainties

Policy implications from spatial disaggregation

- More reliable results help to better estimates the requirement for electric vehicle supply equipment
- It addresses equity issues hidden behind subsidy schemes