High-resolution residential building characteristics and integration with a novel distribution network model

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MITEI Future Energy Systems Center

Electric Power Systems Fall Workshop

December 14 and 16, 2021

Agenda

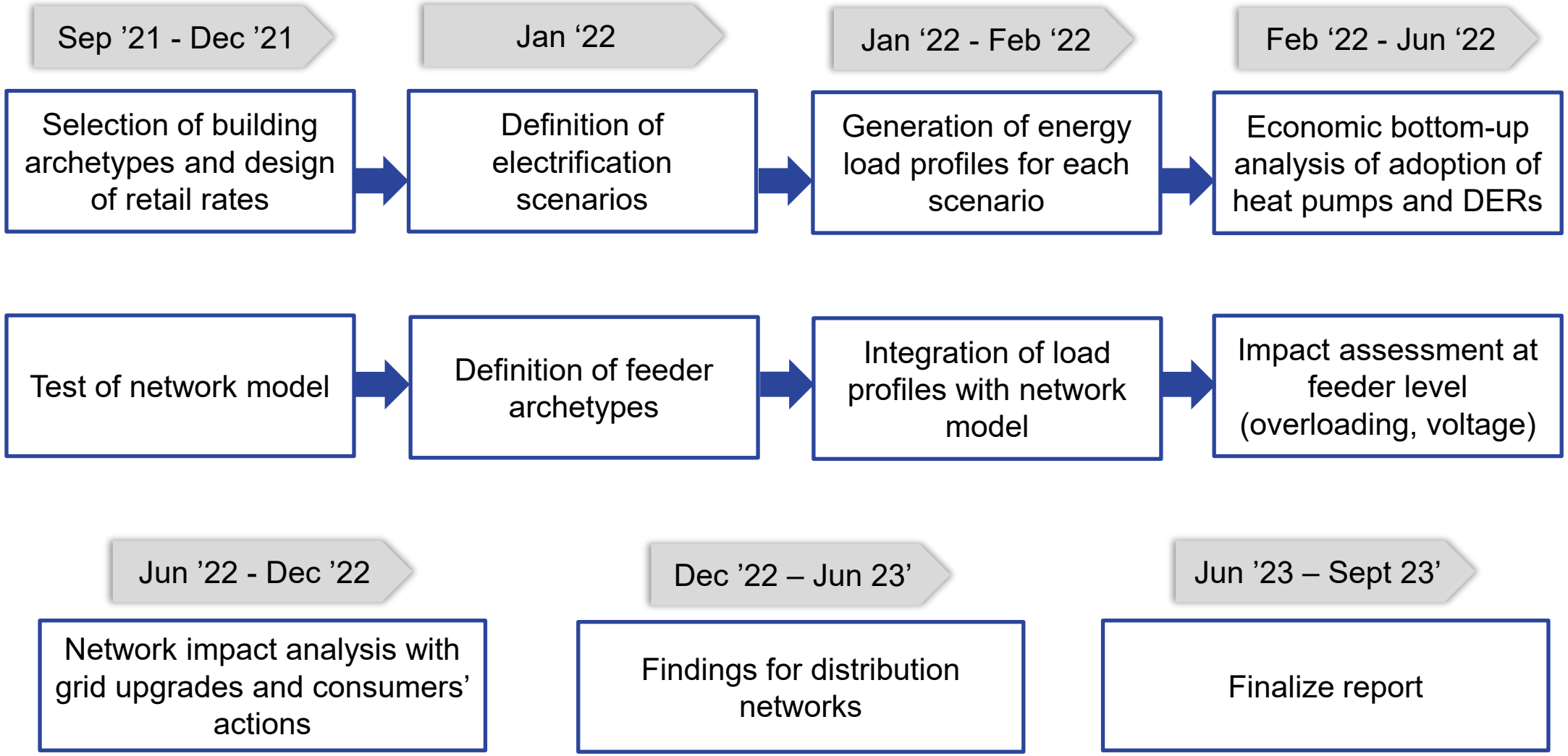
- Research objectives and timeline
- High-resolution building data and economic optimization model
- Integration of electrification load profiles in distribution network model

Research objectives

Impacts of electrification of heat and other end-uses on distribution networks and the role of tariff design in driving the adoption of heat pumps and DERs

- Will consumers adopt a specific technology under different rate designs?
- How will consumers' energy and profiles be after widespread electrification?
- Are current feeders ready to accommodate expected load growth?
- Is there a role for consumer's flexibility in mitigating impacts on the grid?

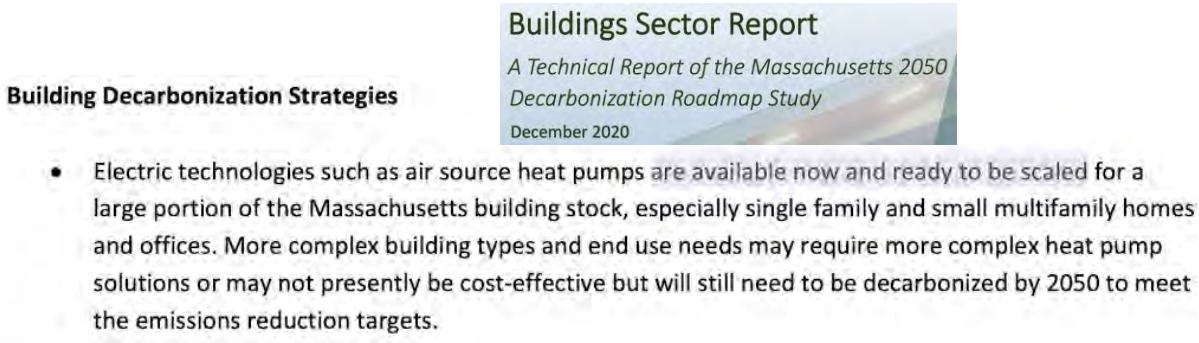
Tasks and tentative timeline



Agenda

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Research Questions





- **How will residential consumers drive *economic* heating emissions reductions from the bottom up?**
  - What is the current distribution of residential heating technologies? → ResStock
  - What does (micro)economically optimal heating emissions reductions look like under current rate structures, installed costs, and building characteristics? → ResStock + DECARB
  - What incentives, subsidies, rate design reforms, are needed to reach electrification goals? → DECARB
  - What are the most cost-effective emissions reductions opportunities in the residential building stock? How do they vary across geography and building type? → ResStock + DECARB

Models

NREL
NATIONAL RENEWABLE ENERGY LABORATORY
ResStock

High-resolution residential building characteristics



Economic optimization of building energy investment and operation

ResStock: High-resolution residential building characteristics

- Synthetic residential building database validated on real data
  - 600,000 residential building profiles
  - 1:250 weight → represents 140 million residential units in the US
  - *Very high geographic resolution*: Public Use Microdata Area (<100,000 population, sometimes an individual city e.g. Cambridge, MA)

- Housing stock characteristics
  - Construction metadata (age, floors, location)
  - Appliances installed (furnaces, boilers, water heaters, dishwashers…)
  - Building envelope specifications (wall material, insulation, window area, presence of ducts)

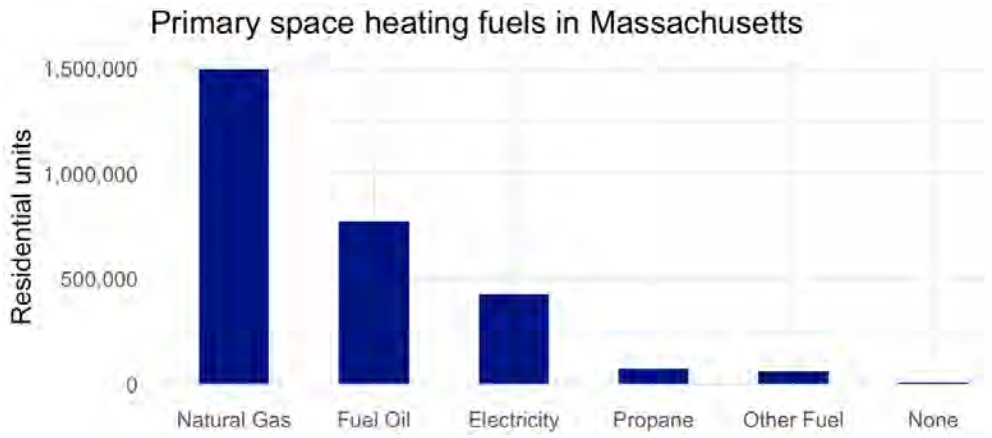
- Granular modeling of load profiles
  - 8760s for 47 detailed end uses (space heating, cooling, clothes drying, hot tub pumps, holiday lights…)
  - Stochastic usage profiles based on American Time Use Survey data

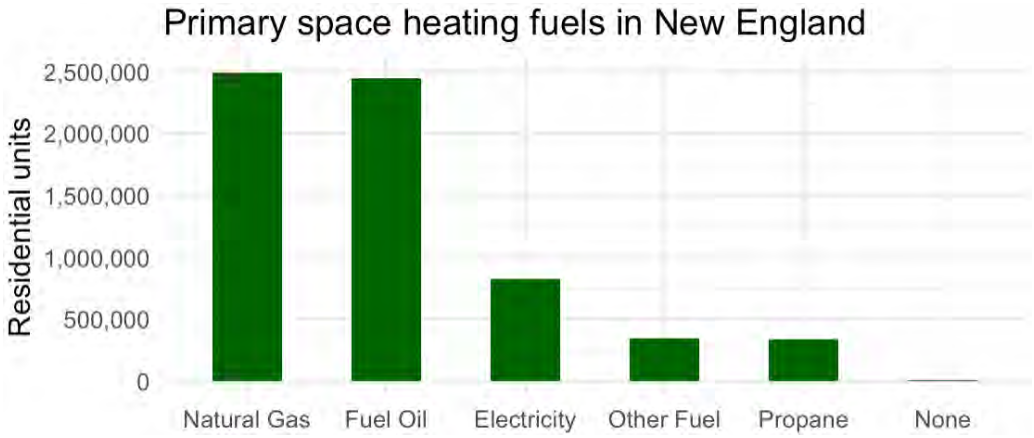


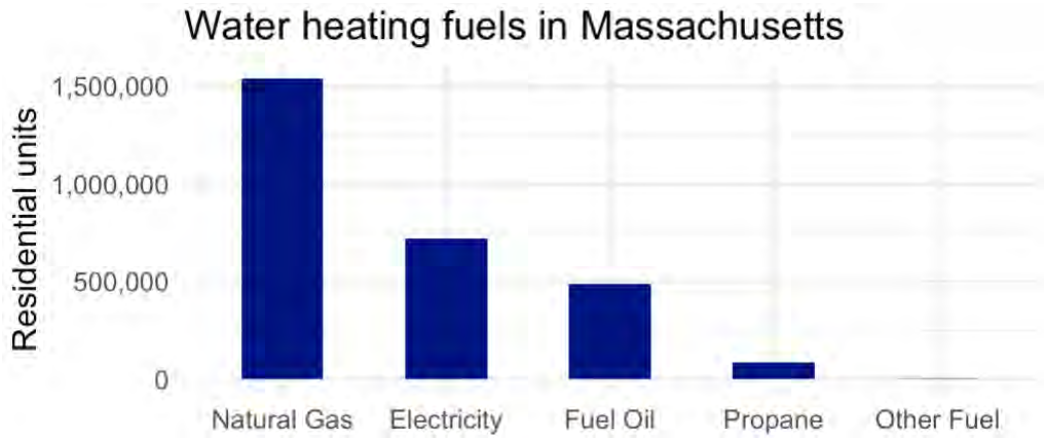
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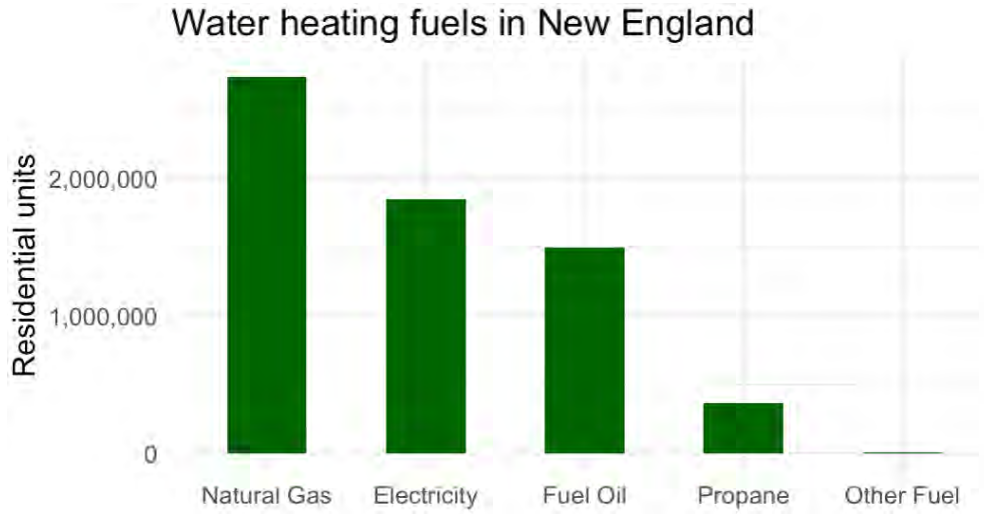
Source: resstock.nrel.gov

ResStock: Heating New England



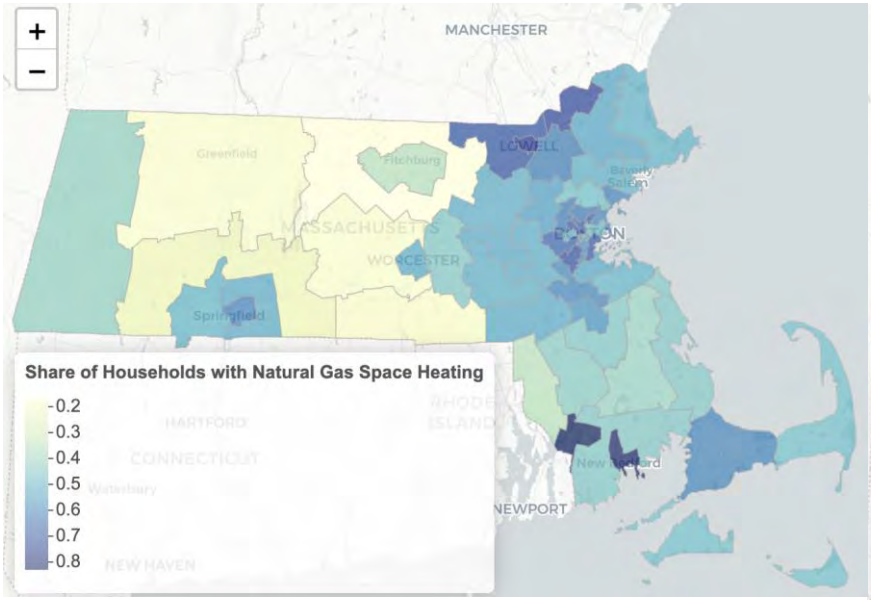


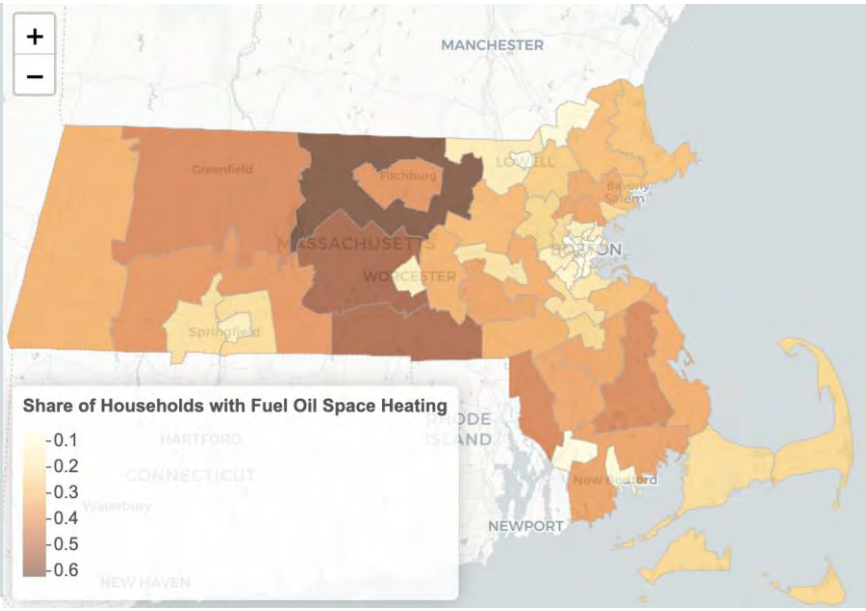


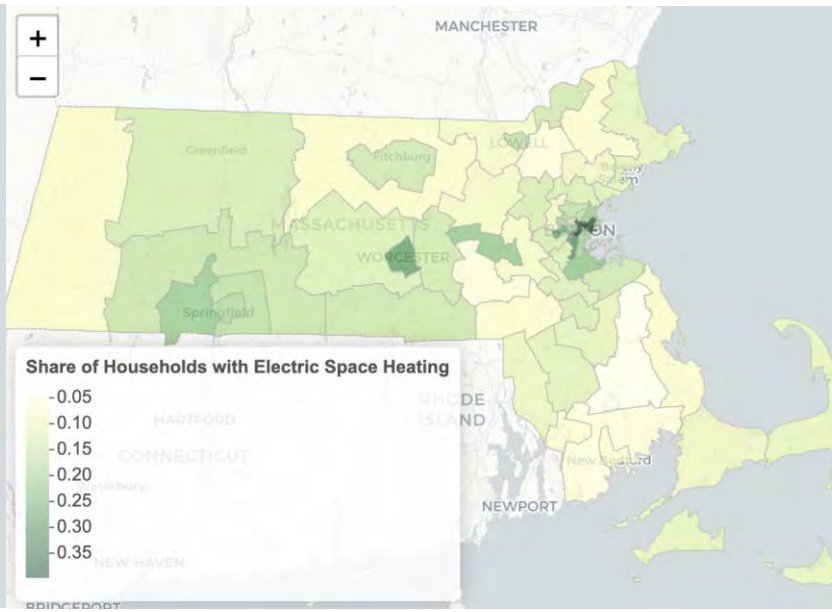


Source: Own analysis based on data from resstock.nrel.gov

ResStock: Heating New England







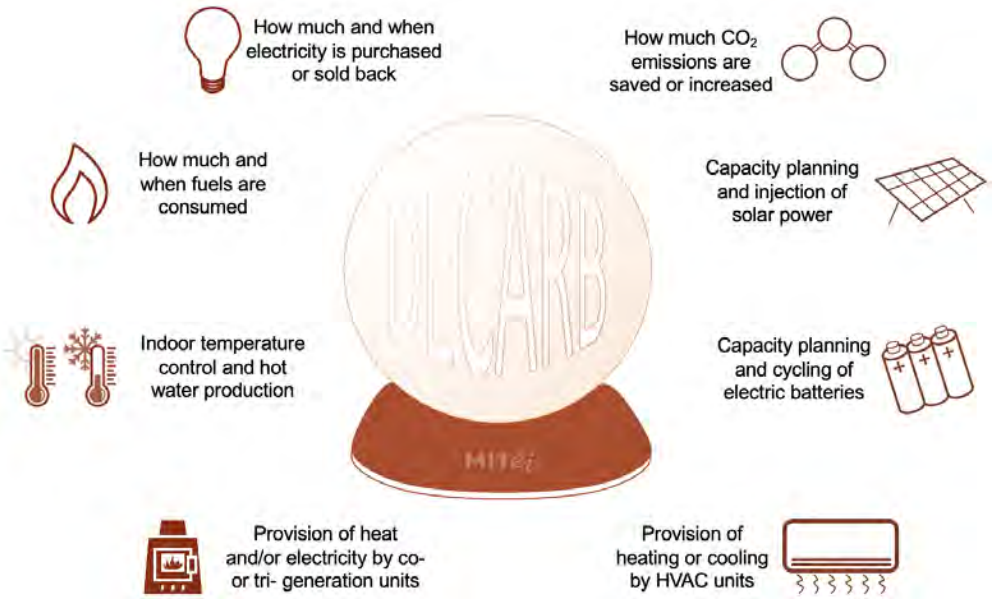
Source: Own analysis based on data from resstock.nrel.gov

DECARB: Distributed Energy Consumption in Actively Responsive Buildings

- What can't ResStock do?
  - Make decisions!
  - ResStock building characteristics database is static
  - No economic model, optimization function, consideration of upgrade costs or utility rates

- MITEI's **DECARB model**: economic optimization of building energy resources
  - Agent-based, building-level model for each of 600k buildings

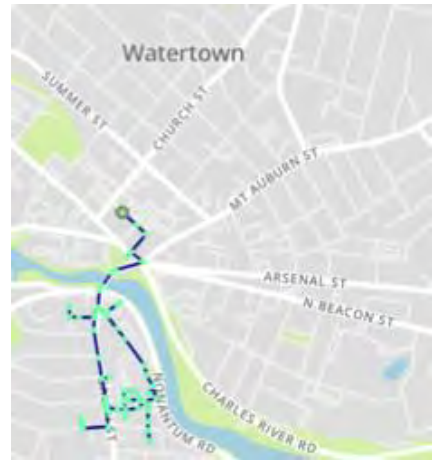
- Integrating ResStock and DECARB
  - ResStock building characteristics can be used as inputs for DECARB
  - Individual optimization models for each of 600k buildings
  - Then, we can use DECARB to model bottom-up adoption of residential electrification upgrades
  - Test different rate designs, appliance costs, policy incentives, emissions regulations…



ResStock & DECARB Integration

NREL
NATIONAL RENEWABLE ENERGY LABORATORY
ResStock





Building characteristics, installed appliances, uncontrollable load profiles, stochastic usage profiles

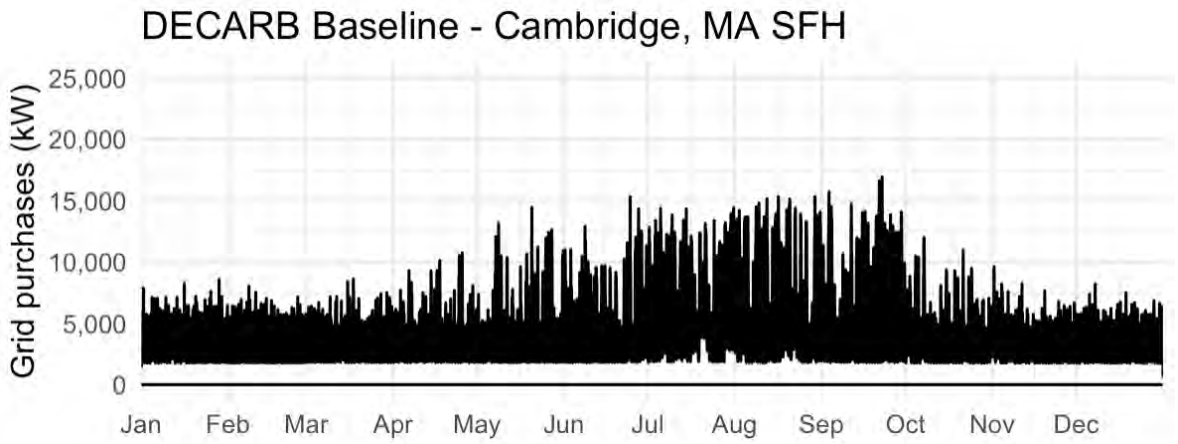
Investment and operation of building energy resources, financials (NPV & payback period), grid purchase profiles

Distribution system impacts

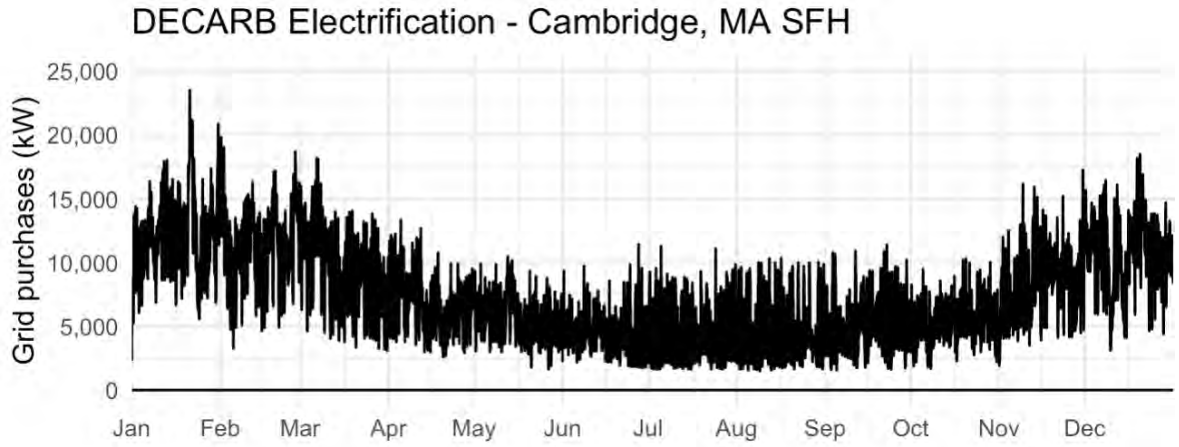
MITei

ResStock Baseline vs. DECARB Electrification

- ResStock baseline inputs of 20 SFH archetypes in Cambridge, MA (~5000 houses)



- 100% “forced” space & water ASHP electrification of 20 SFH archetypes in Cambridge, MA (~5000 houses)



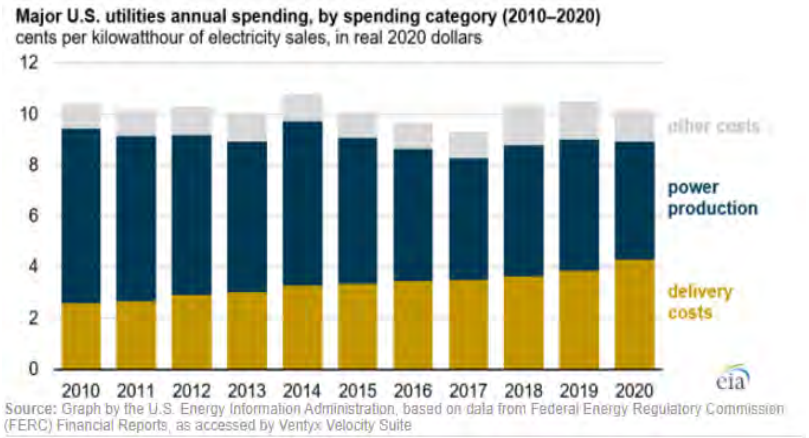
Ongoing Research

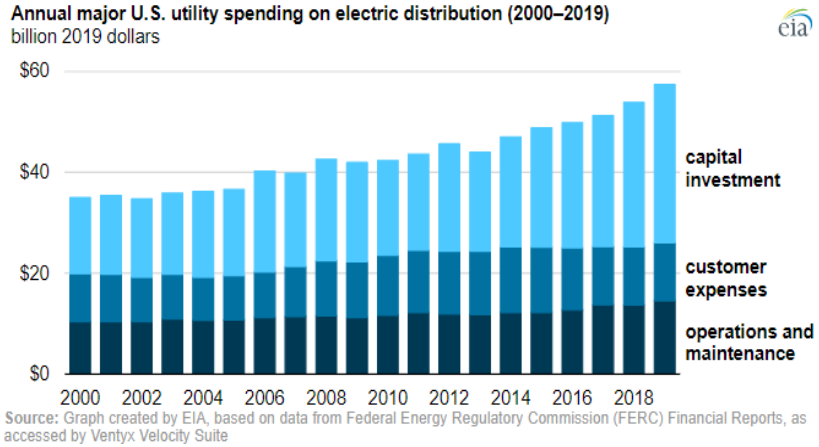
- Integration of ResStock → DECARB nearing completion
- Undertaking DECARB codebase improvements to speed up iteration
- **We need high-quality cost data for installed upgrades**
- Model granular optimal economic response to changes in rate structures
- E.g. What subsidy level is *required* to achieve Massachusetts' electrification goals?
- Integrate outputs with distribution network modeling to explore the impacts of economical electrification on distribution upgrade costs → Tony Lee

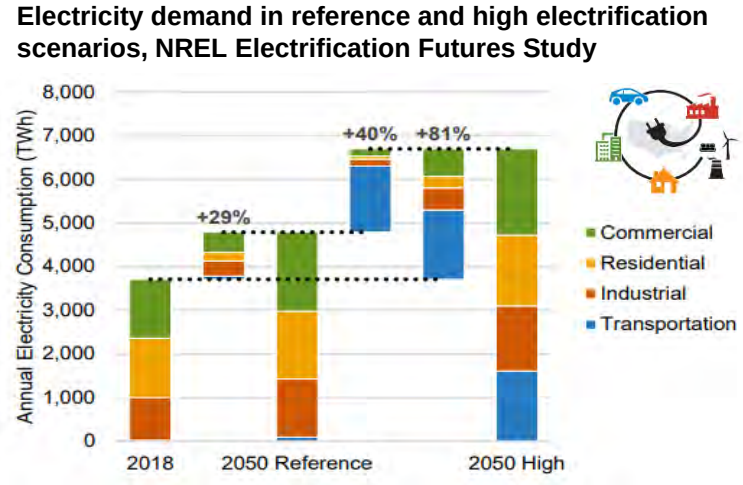
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The distribution system accounts for a growing share of U.S. electricity costs even before widespread electrification







- Transmission and distribution costs account for over 40% of delivered cost of electricity nationally in 2020.
- Utility spending on electric distribution has steadily increased despite flat consumption. However, most distribution investment today is for replacing aging infrastructure, rather than to accommodate load growth.
- Widespread electrification would increase load by as much as 80% per NREL electrification futures study.
- What are the impacts of heating (and transport) electrification on energy demand and distribution infrastructure needs?
- What are the resiliency implications of residential heating and transport electrification?
- Can distributed energy resources and demand-side flexibility improve social outcomes and mitigate these impacts?

Sources: EIA, Today in Energy; NREL, Electrification Futures Study: Operational Analysis of U.S. Power Systems with Increased Electrification and Demand-Side Flexibility.

Model Summary

- MITEI researchers, principally PhD student Marc Barbar, developed a novel distribution network model to **simulate power flows**, **identify constrained elements**, and **optimally reinforce the network** with energy storage or traditional distribution upgrades.

- Developed in **Python**, leveraging **pandapower** package for power systems analysis and optimization
  - *L. Thurner, A. Scheidler, F. Schäfer et al, pandapower - an Open Source Python Tool for Convenient Modeling, Analysis and Optimization of Electric Power Systems, in IEEE Transactions on Power Systems, vol. 33, no. 6, pp. 6510-6521, Nov. 2018.*



- Model is described further in
  - *Barbar, Marc, Mallapragada, Dharik, Stoner, Robert, Perez-Arriaga, Ignacio. (2021). Distribution level battery storage valuation framework. https://arxiv.org/abs/2106.07590*
  - *Upcoming MITEI Future of Energy Storage study*



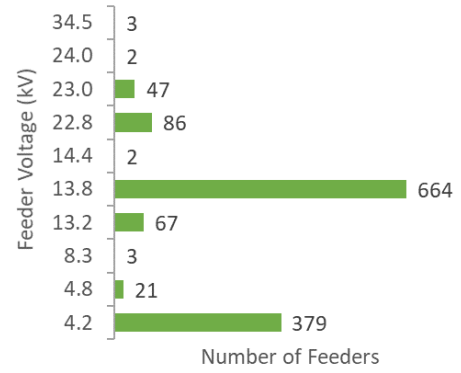
Research Scope and Methodology

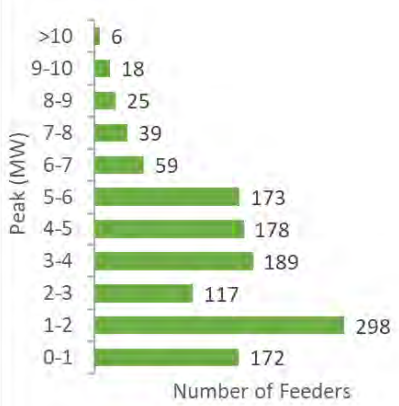
- **Assess the distribution-level impacts of residential heating electrification in the Northeast U.S. and quantify the distribution value of demand-side solutions.**
  1. Run power flow on reference case, reinforce if necessary, establish baseline costs
  2. Run power flow on each electrification scenario, reinforce if necessary, calculate upgrade costs
  3. Calculate modified electrification load profiles stacking up demand-side solutions, run power flow, check if reinforcement is still needed
     a. Energy efficiency
     b. Load shifting through time-of-use tariffs
     c. Rooftop PV
     d. Battery storage
     e. Backup generation
  4. Estimate distribution value of demand-side solutions under heating electrification as difference between investment costs
- **Simulate user investment in local backup generation under electrification scenarios**
  1. Define residential value of lost load (VOLL) as function of outage duration, peak demand and add to agent-based optimization
  2. Impose grid disconnection of some X consecutive hours (with perfect foresight)
  3. Calculate optimal investments under electrification with quantification of resilience benefits

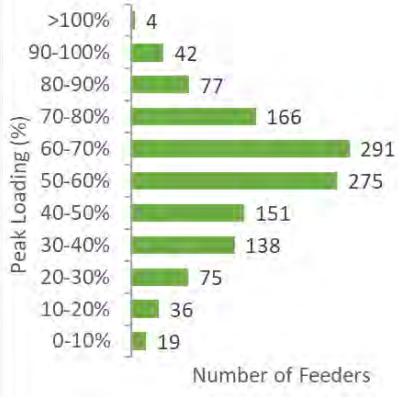
Current Data Sources

- Distribution feeder data for Massachusetts was scraped from Eversource and National Grid hosting capacity maps
  - n = 1,274 Eversource, 1,326 National Grid
  - Load on each feeder is 2019 non-coincident peak (but no data on when these peaks occurred)
  - Peak loading represents maximum loading on any element of feeder
- Majority of feeders in current data are 13.8 kV or 4.16 kV
- Some motivating questions:
  - Most elements feeders have some amount of headroom (at summer peak?)
  - How do these loadings change with heating electrification?
  - What are the archetypes of feeders that are most ready and least ready for electrification?

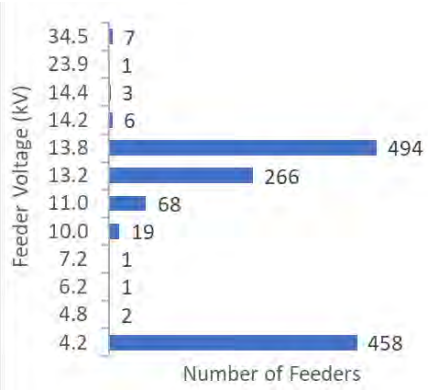
Eversource

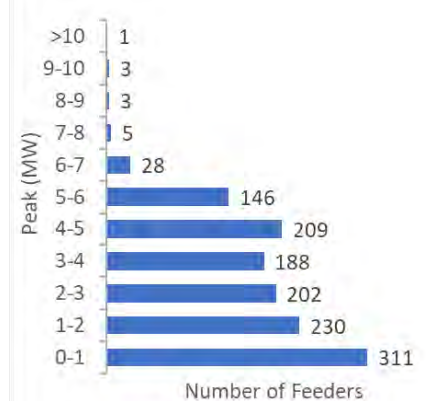


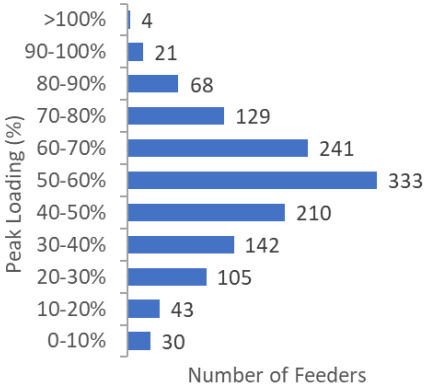




National Grid

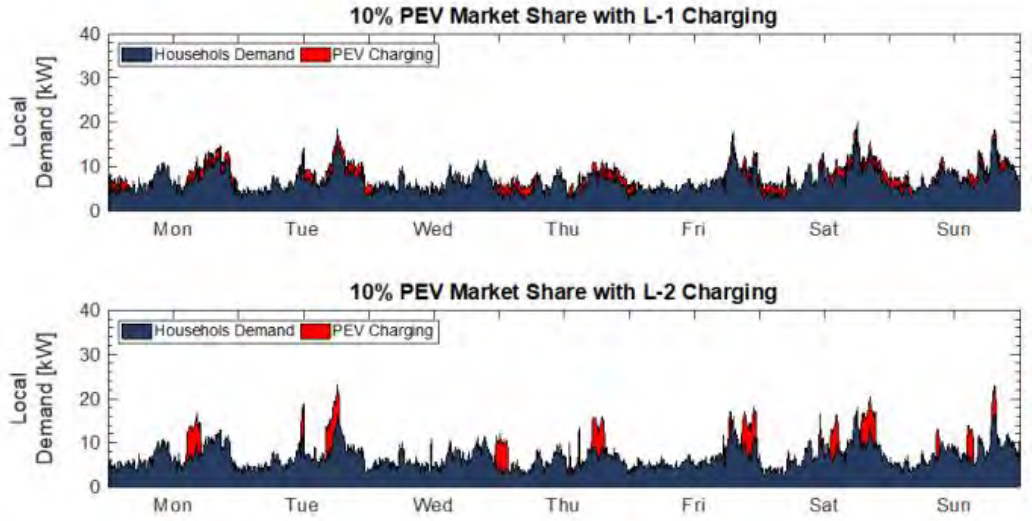




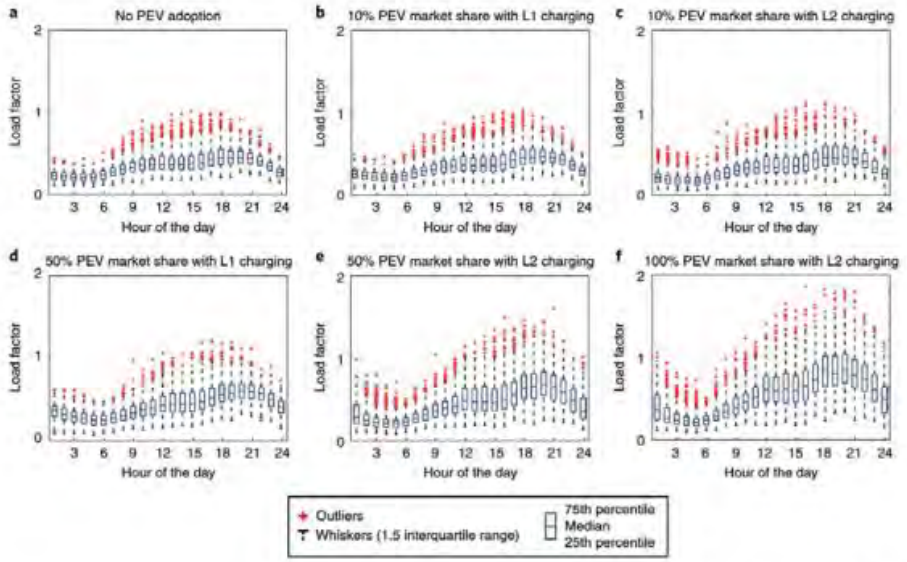


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  - Peak loading represents maximum loading on any element of feeder
- Distribution reinforcement costs from NREL's *2019 Distribution System Upgrade Unit Cost Database*
  - "Data collected from variety of utilities, developers, vendors, and published research reports"
- Baseline residential EV charging load from
  - Muratori, M. Impact of uncoordinated plug-in electric vehicle charging on residential power demand. *Nat Energy* **3,** 193–201 (2018). https://doi.org/10.1038/s41560-017-0074-z
  - Data for 200 households: https://data.nrel.gov/submissions/69
- We are very receptive to sponsor suggestions and improvements to these data sources



Source: Muratori 2018

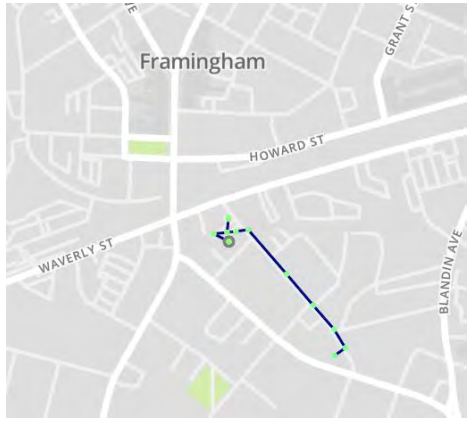


Source: Muratori 2018

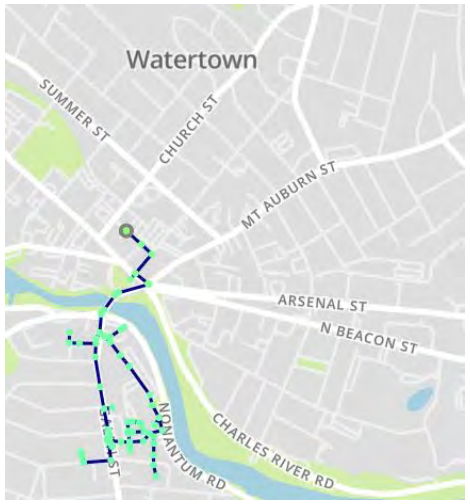
$$Load\ factor = \frac{hourly\ power\ consumption}{transformer\ nominal\ power}$$

Examples of Distribution Feeder Power Flows Before Electrification

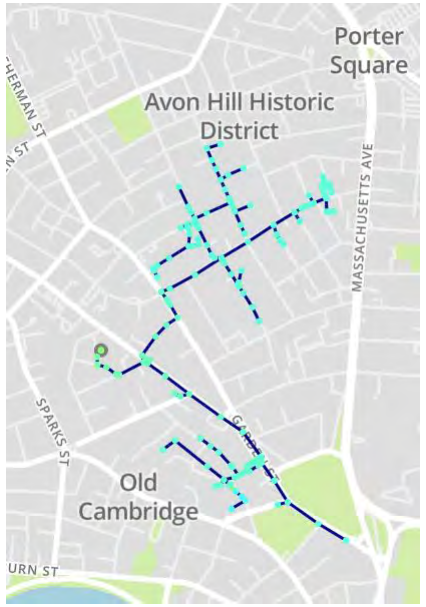
4.16 kV, 2.2 MW peak Framingham feeder

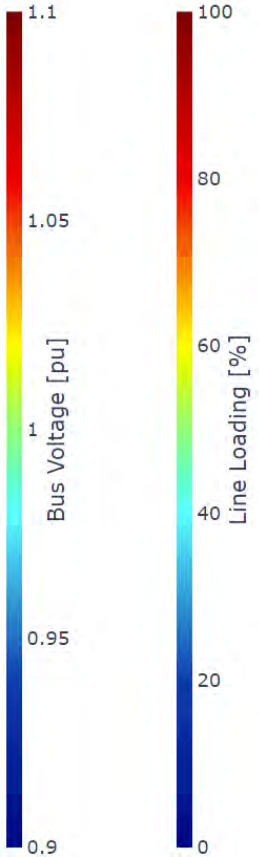


4.16 kV, 1.5 MW peak Watertown feeder

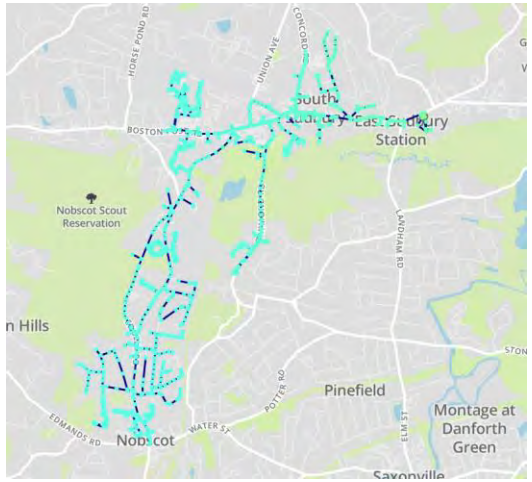


4.16 kV, 2.0 MW peak Cambridge feeder

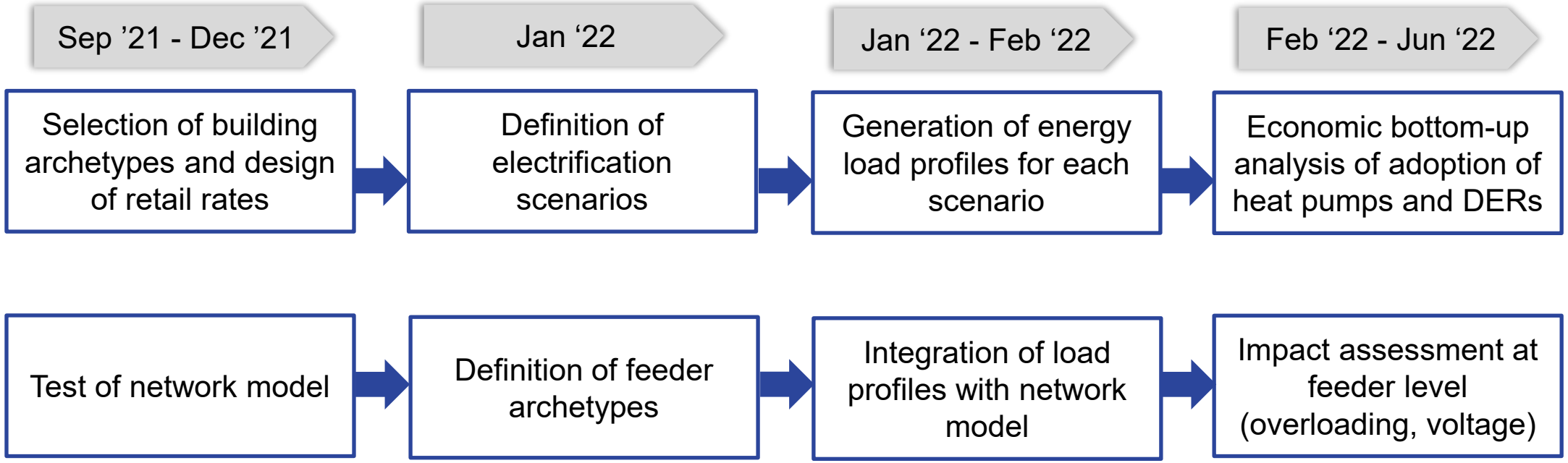




13.8 kV, 3 MW peak Sudbury feeder



Ongoing Research



- Use clustering to identify archetypes of distribution feeders in current dataset
- Incorporate baseline and electrification load profiles from DECARB scenarios
  - Allocate buildings profiles to feeder by matching peak loads
  - Populate feeder archetypes with building profiles to capture MA diversification
  - Analyze feeder status before and after electrification
- Impact assessment of heating electrification at the feeder level