



# Interaction Effects between Battery Electric Trucks, Electric Road Systems and Static Charging Infrastructure

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*Finansieras av ERUF och Region Blekinge*



# **Interaction Effects between Battery Electric Trucks, Electric Road Systems and Static Charging Infrastructure**




**Jakob Rogstadius,  
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# Background

- Road traffic contributes 20% of EU GHG emissions. Share is increasing. 30% from heavy trucks.
- GHG emissions from Swedish road traffic should decrease by 70% by 2030 vs. 2010.  
20% achieved by 2019, mainly through biofuels
- Today in Sweden
  - >50% of passenger car sales are BEV
  - <1% of heavy truck sales are BEV



# Charging Infrastructure Landscape

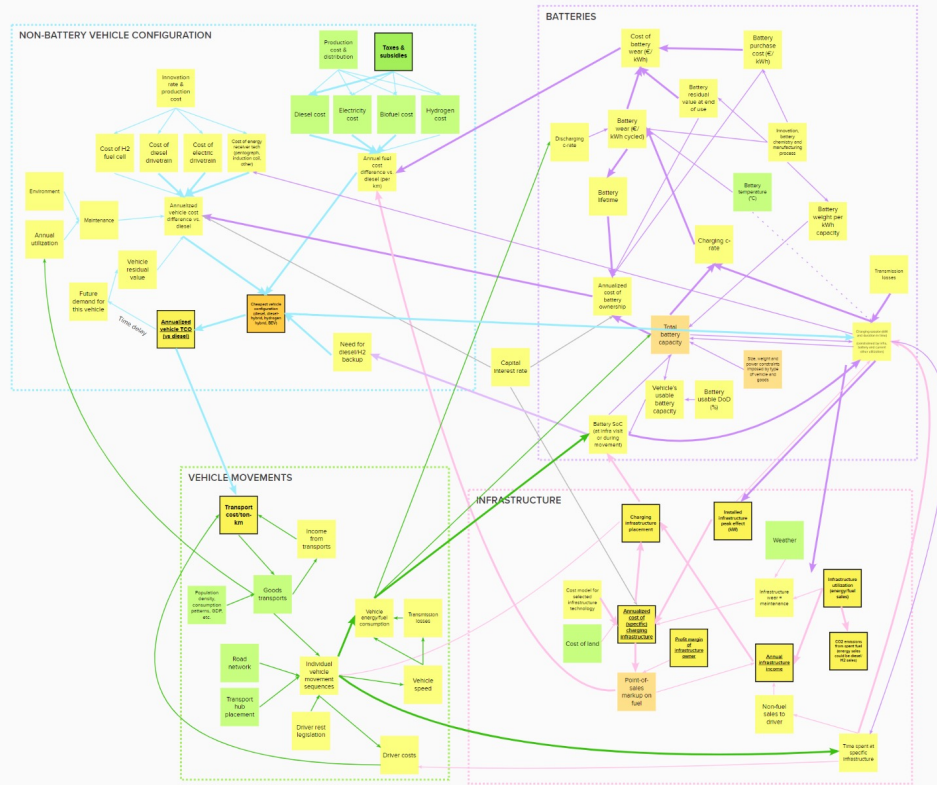
- Maturing for passenger cars
- Current approach to electric heavy trucks:  
large batteries + depot charging + fast charging stations
- Electric Road Systems (    ) proposed
- Infrastructure should last 15-40 years, despite changing battery technology and growing density of EV population and chargers



# Electric Truck Charging – a Complex System

Prior work has generally ignored:

- Distributed decision making
- Interaction effects
- Feedback loops
- Pivot points
- Non-linear emergent behavior



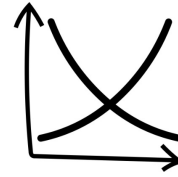
# Scope: Capture the System Dynamics



Four heavy truck  
classes share  
infrastructure



Millions of  
overlapping  
transport routes



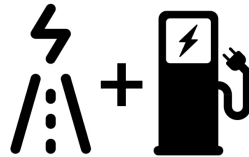
Supply, demand  
and user charges  
in balance



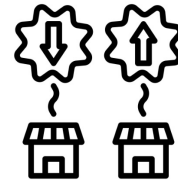
Lifecycle battery  
costs determined  
through use



Entire Swedish  
road network



Combinations of  
static and dynamic  
charging



Competing  
charging  
infrastructure,  
built over time

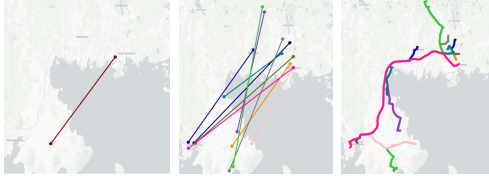


Tax revenue kept  
unchanged

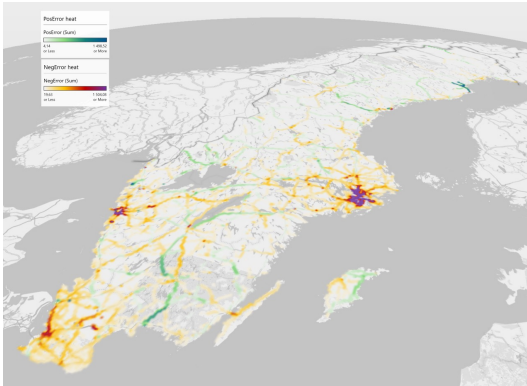
# Method



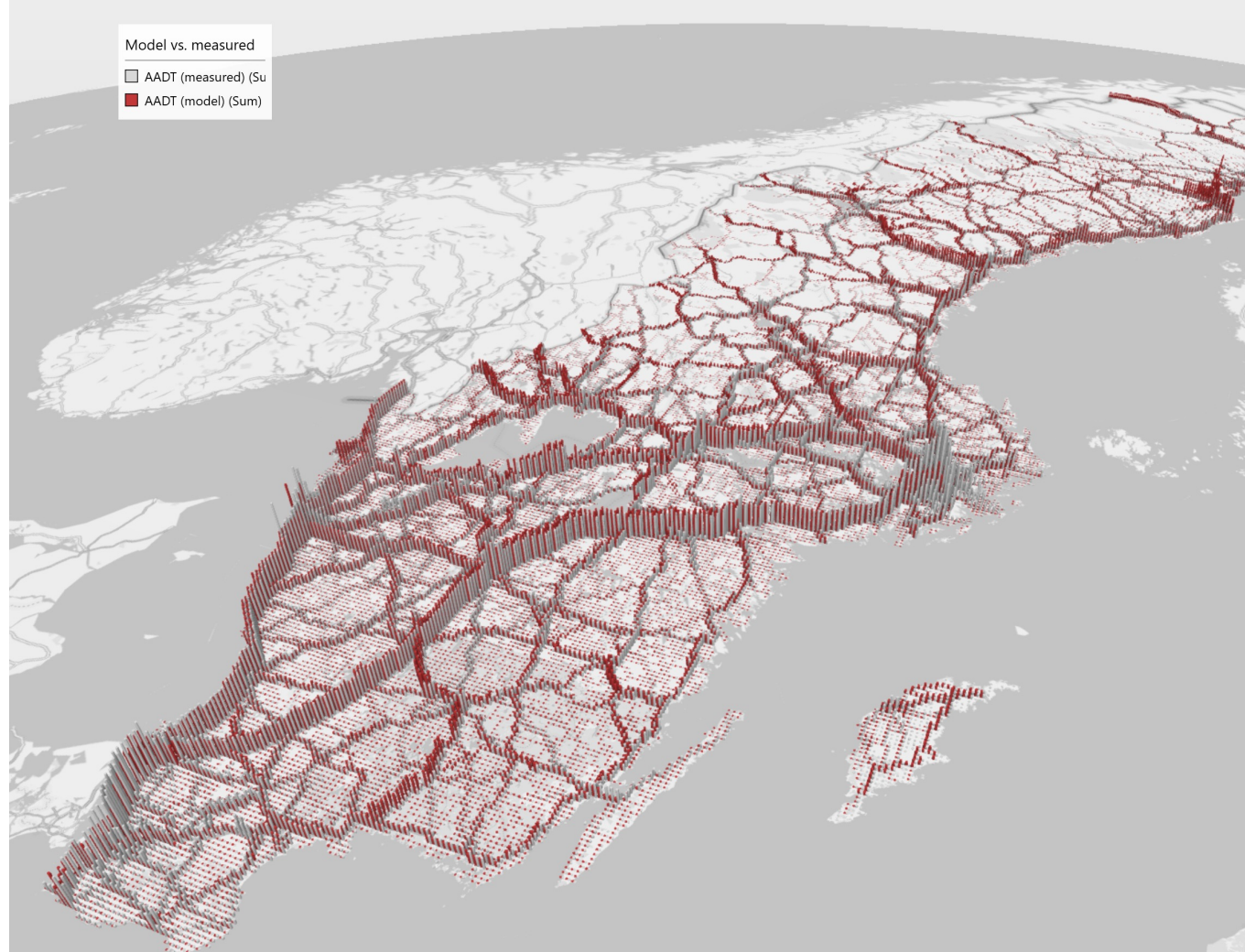
## Traffic data: 200k goods flows → 2M routes



Sampling of route variants for a pair of municipalities, followed by routing along the road network



Underestimates (red) and overestimates (green) of traffic density on the road network. Underestimates may be due to lack of bus traffic.



Comparison after data calibration with measured AADT

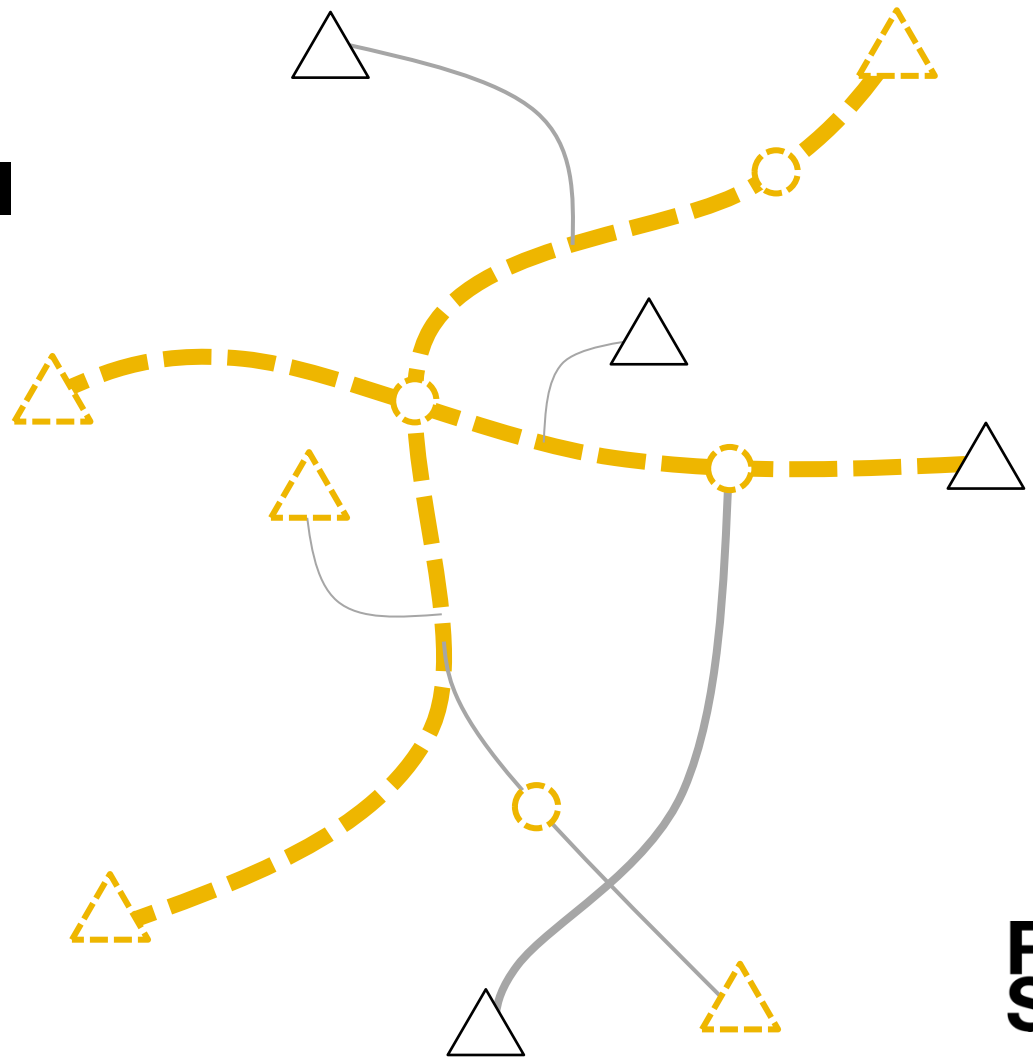
# Simulation model

Offer candidate locations where charging infrastructure can be built this model year.

For every route and vehicle class, choose the combination of battery capacity and charging strategy that minimizes cost.

Build charging infrastructure.

Add up system cost.



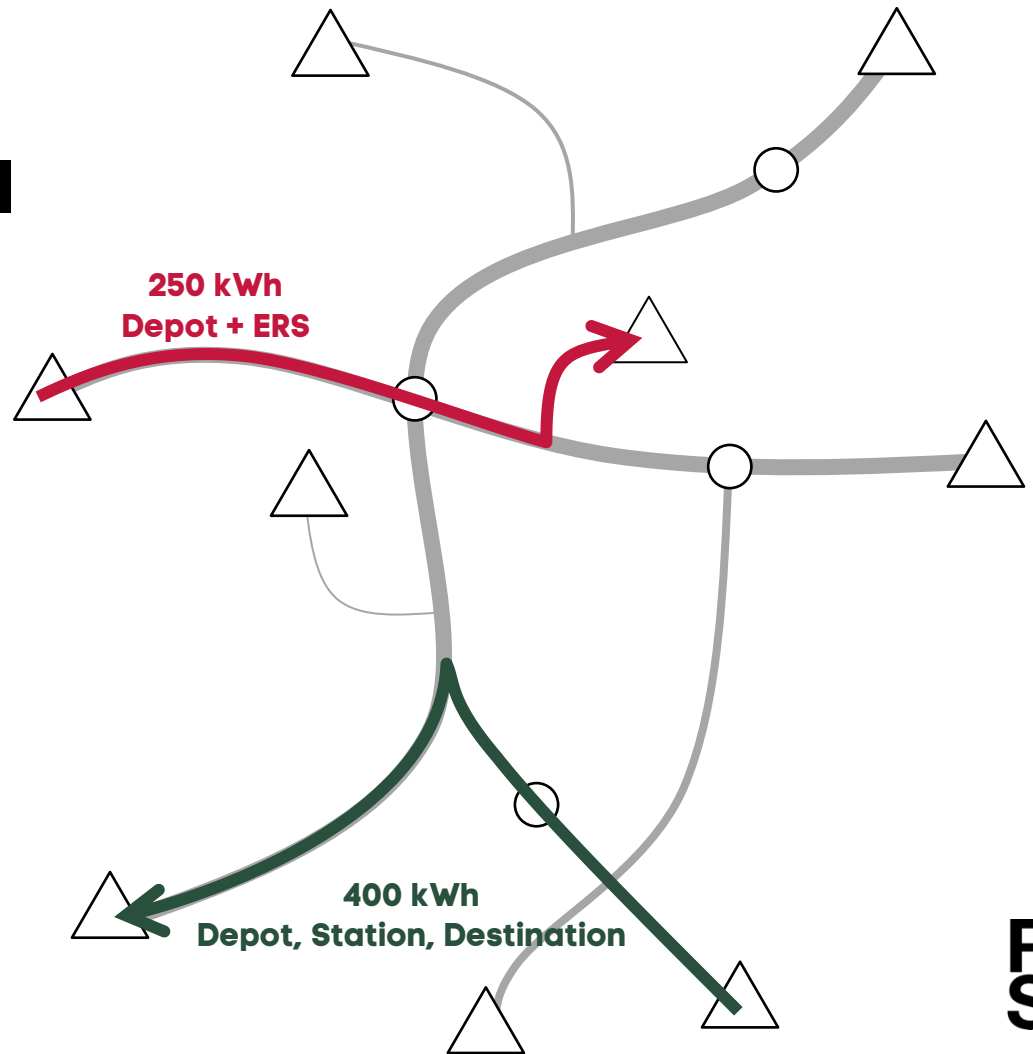
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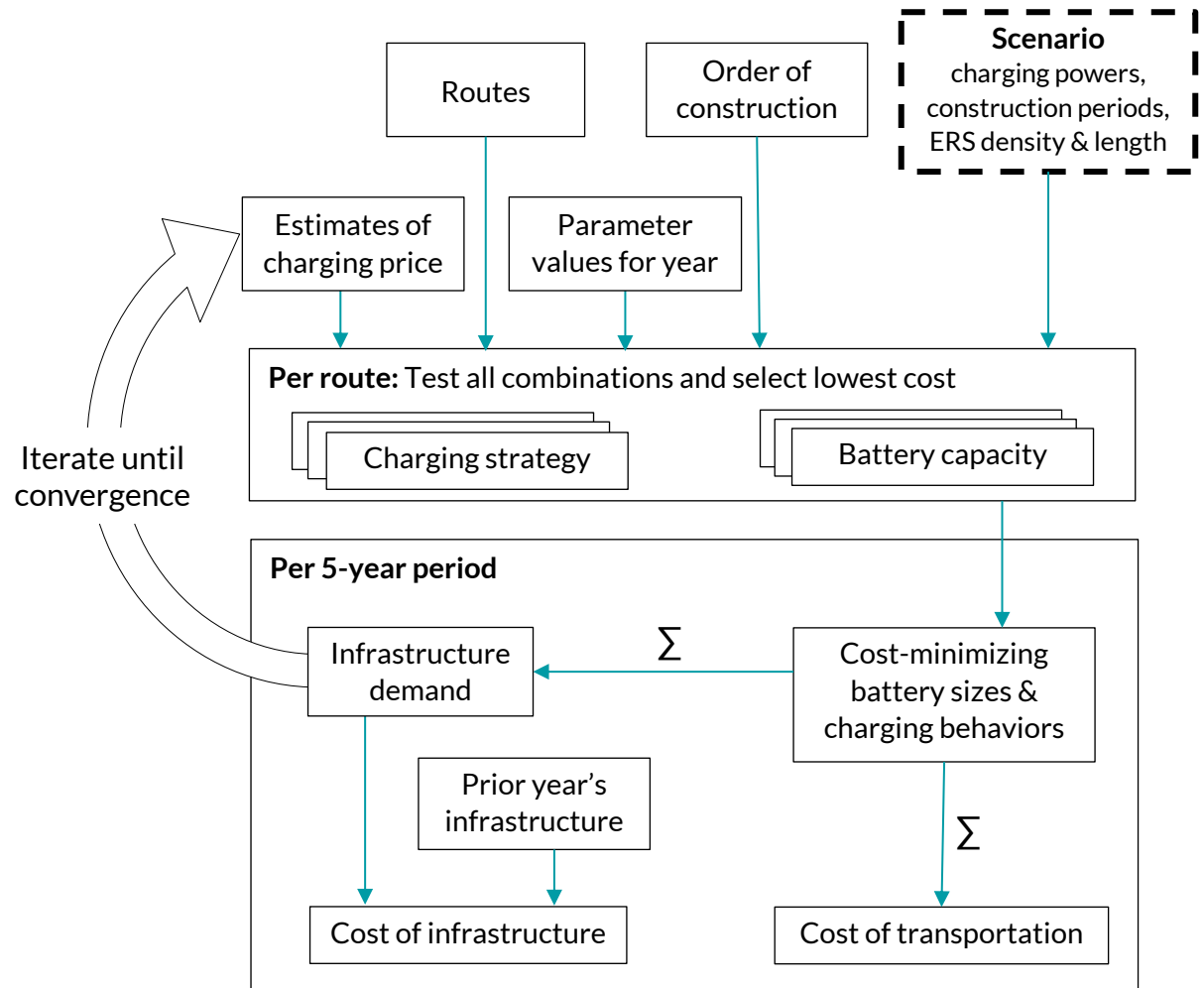
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# Simulation model

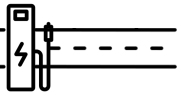


# Four charging alternatives along routes

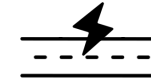
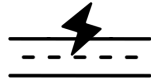
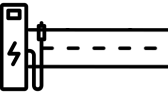
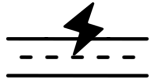
## 1. Depot charging



## 2. Fast charging stations



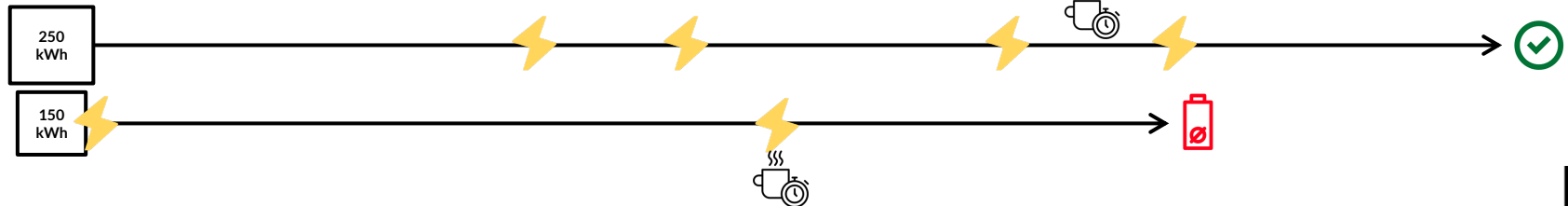
## 3. ERS segments



## 4. Destination charging



## Charging strategy





# Parameter assumptions, charging infrastructure @ Y2020

| Placement   | Base cost    | Power cost  | Write-off time | Maintenance | Risk | Utilization | Pick-up, base | Pick-up, power | Interest rate |
|-------------|--------------|-------------|----------------|-------------|------|-------------|---------------|----------------|---------------|
| Depot       | 10000 €/site | 400 €/kW    | 5 years        | 10 %/year   | 0    | 44%         | -             | -              | 12 %/year     |
| Destination | 10000 €/site | 600 €/kW    | 10 years       | 10 %/year   | 0    | 27%         | -             | -              | 6 %/year      |
| Station     | 20000 €/site | 600 €/kW    | 20 years       | 10 %/year   | 0    | 43%         | -             | -              | 6 %/year      |
| 2-way ERS   | 1.2 M€/km    | 250 €/kW-km | 30 years       | 2 %/year    | 15 % | 43%         | 2000 €/truck  | 50 €/kW        | 2 %/year      |

## Other important assumptions

ICEV lifespan = 7-10 years

BEV lifespan = 7-10 @ Y2020 → 12-15 years @ Y2035

Battery pack lifespan = calculated from use

Min. battery pack output = 160, 300, 550, 750 kW (16-60 ton)

Battery pack cost = 160 → 34 €/kWh (part of battery TCO)

Biofuel ratio in diesel = 25% → 77%

CO<sub>2</sub> sources = fossil and biofuels, Nordic energy mix, battery prod.

CO<sub>2</sub> = 0.7€/kg SCC, taxation 12% → 42% of SCC

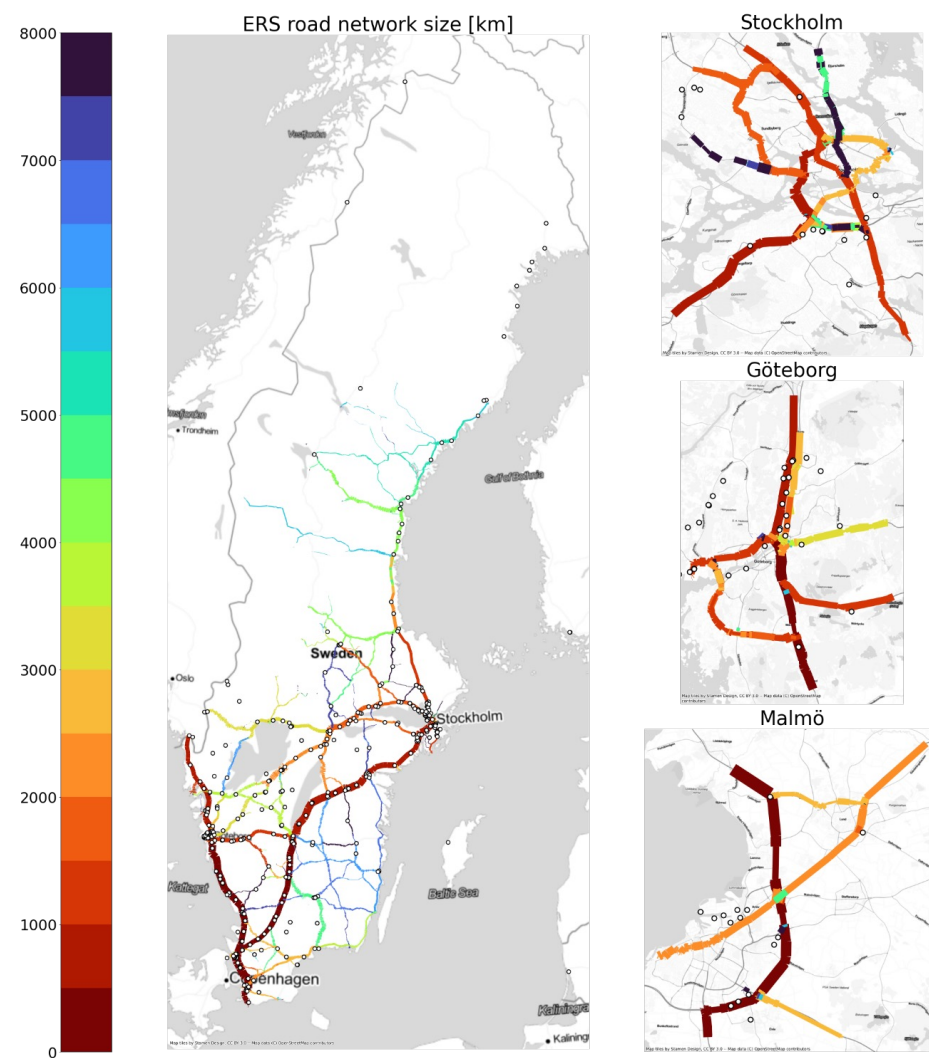
# Results

Where should ERS infrastructure be placed?



# Order of infrastructure construction

- Map shows pre-calculated ERS segment order
- Fast charging stations at locations identified by ACEA, in decreasing order of AADT
- Segments and sites are skipped when highly unprofitable
- Order of depots and destinations is random



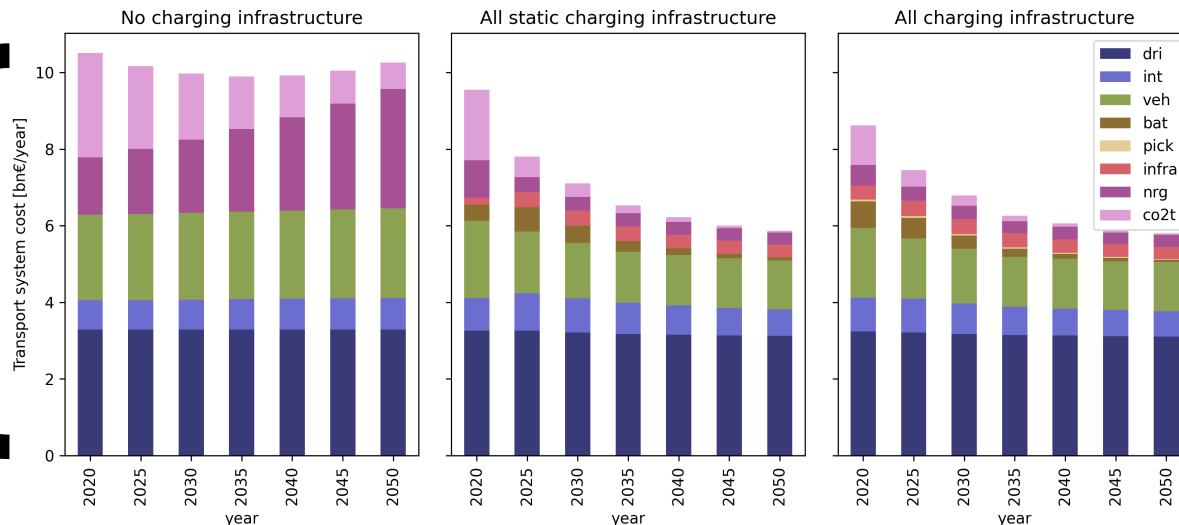
What range of results are possible?

Can ERS generate socio-economic savings compared to electrification without ERS?

## Experiment

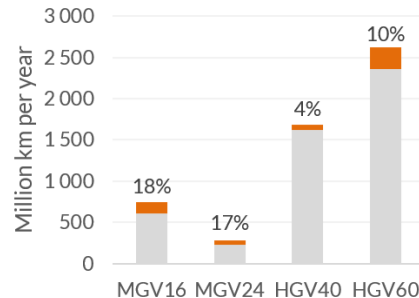
# Possible spread of system cost given model and input parameters

Annual system cost



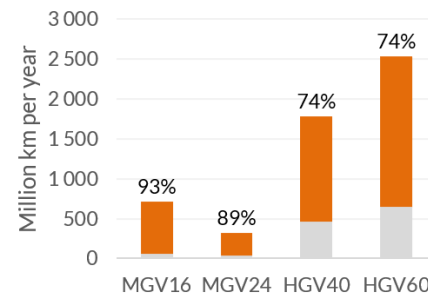
## 25% depot @ Y2020

■ Diesel ■ Electric



## Charging everywhere @ Y2020

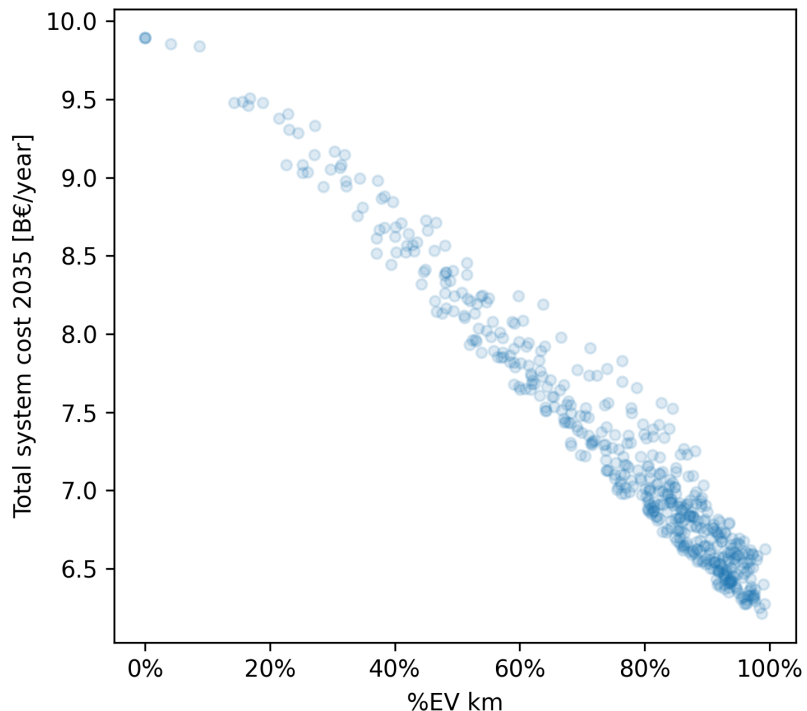
■ Diesel ■ Electric



## Experiment

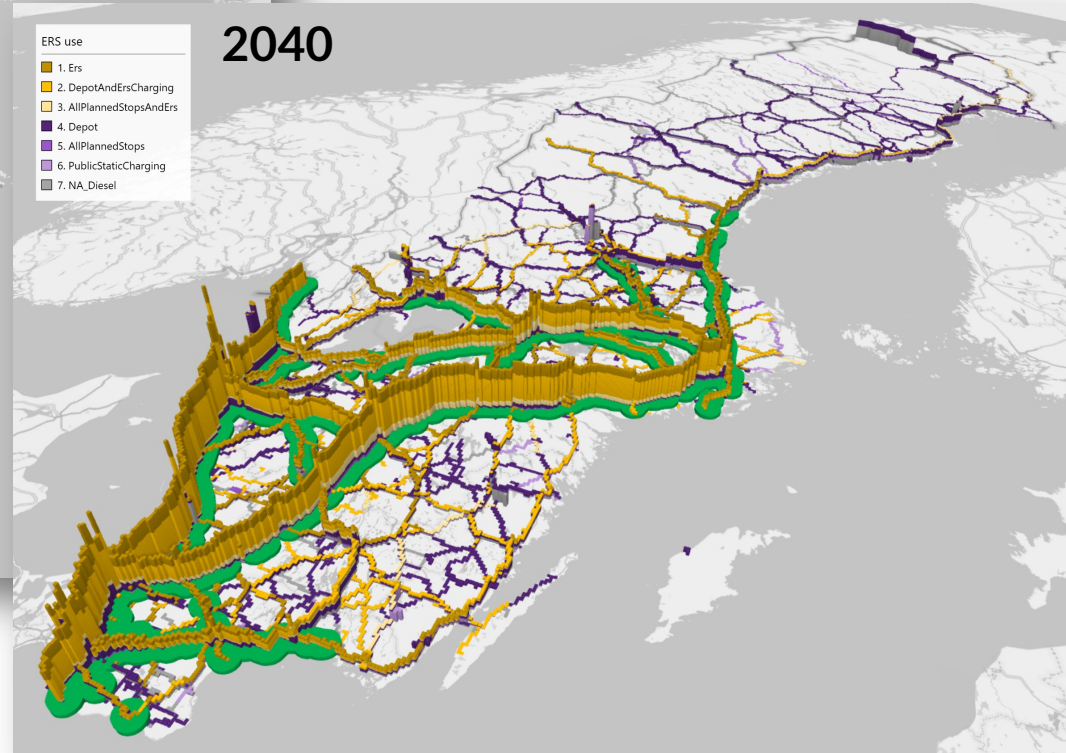
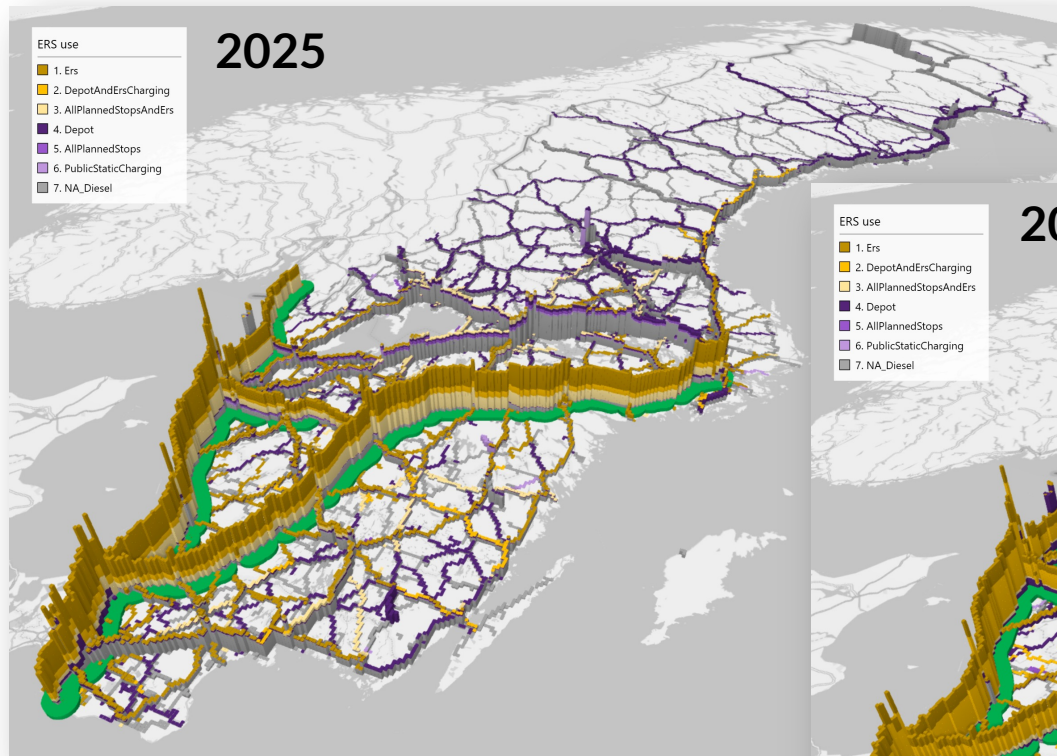
# Electrification = cost reduction

- 513 scenarios, year 2035, varied charging infrastructure
- System cost depends mostly on ratio of traffic electrified
- Several scenarios can minimize system cost, but many are unrealistic. Other qualities differ.



If system cost can be minimized without ERS,  
does nobody want it?

# Almost all heavy traffic uses ERS where available



What competitive advantage does ERS offer  
vs. other charging infrastructure?

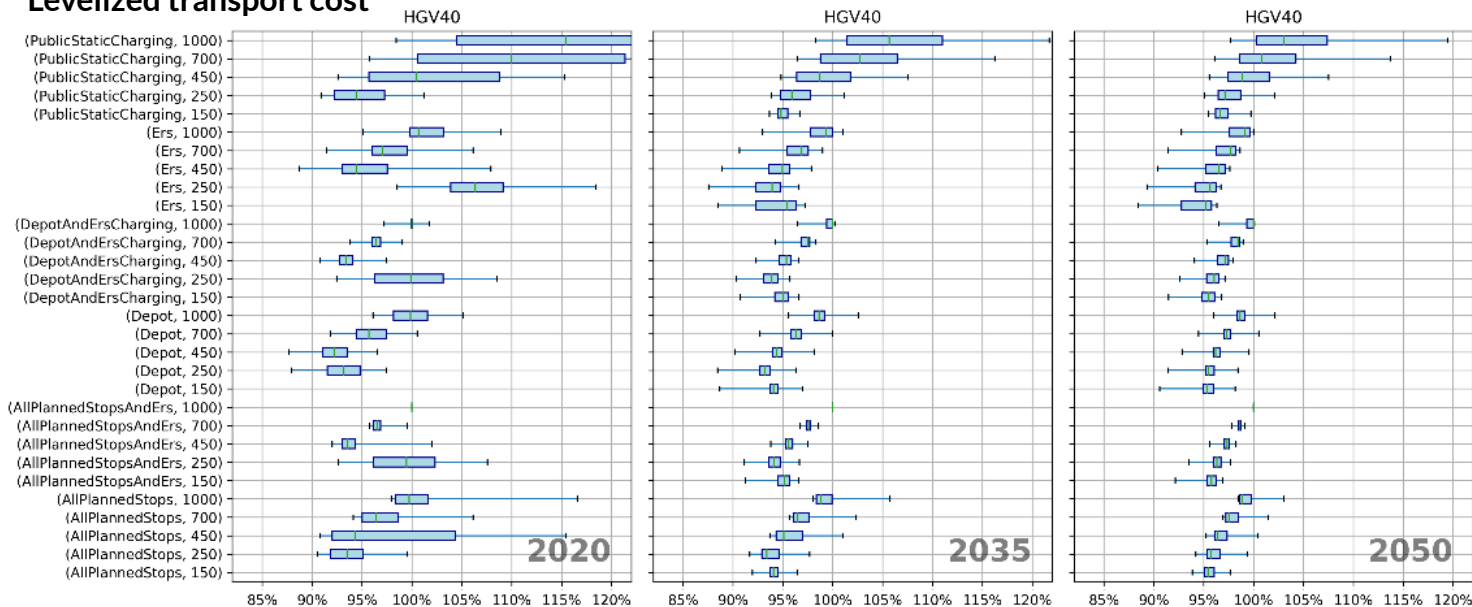


## Experiment

# Why is ERS attractive?

- ERS makes smaller battery packs viable
- Smaller battery packs reduce levelized transport cost (positive contribution from capital interest, calendar ageing and weight)

## Levelized transport cost



## Viable percent of routes

### Charging strategy

AllPlannedStopsAndErs  
 DepotAndErsCharging  
 AllPlannedStops  
 Ers  
 Depot  
 PublicStaticCharging

|                       | 150 kWh | 250 kWh | 450 kWh | 700 kWh | 1000 kWh |
|-----------------------|---------|---------|---------|---------|----------|
| AllPlannedStopsAndErs | 37      | 60      | 83      | 92      | 94       |
| DepotAndErsCharging   | 33      | 53      | 71      | 82      | 86       |
| AllPlannedStops       | 8       | 17      | 60      | 81      | 89       |
| Ers                   | 18      | 32      | 44      | 48      | 51       |
| Depot                 | 7       | 13      | 28      | 48      | 65       |
| PublicStaticCharging  | 1       | 3       | 7       | 13      | 17       |

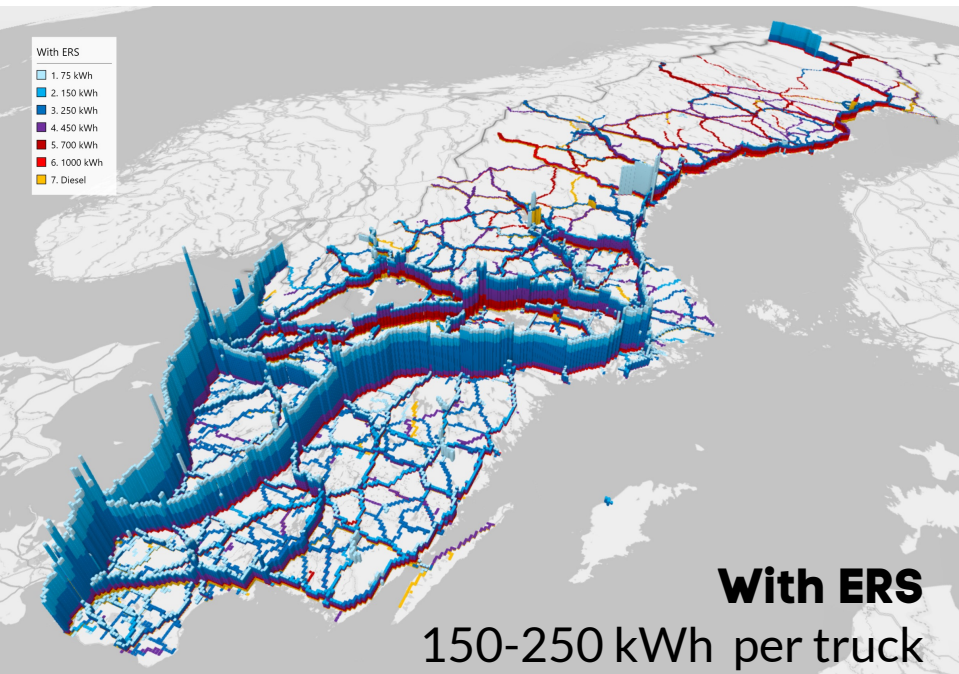
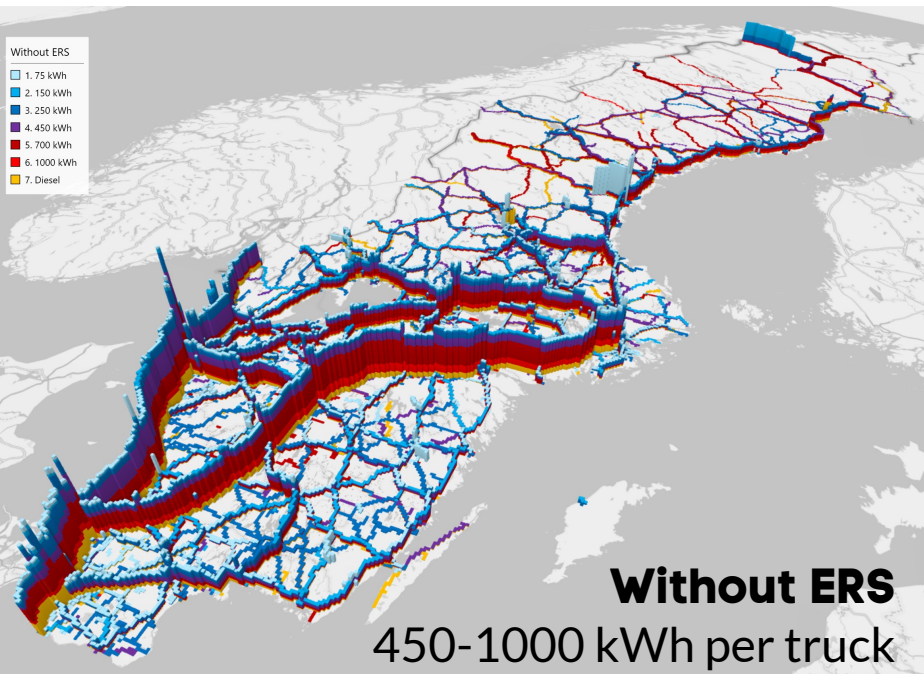
How does ERS affect sizing and ageing  
of battery packs in trucks?

## Experiment

# Battery capacity per truck

Smaller batteries reduce

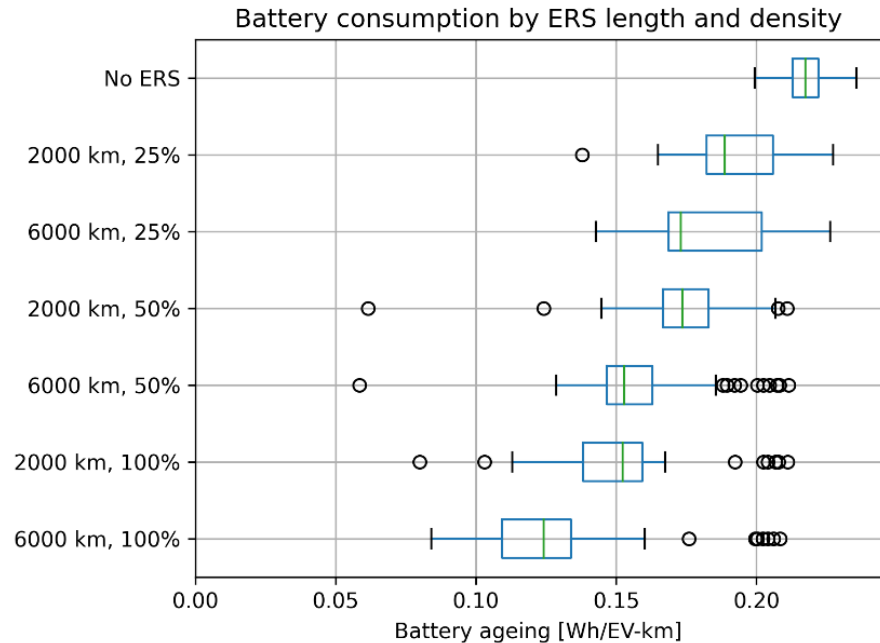
1. cost of capital
2. cost of calendar ageing
3. trips required to move total cargo



## Experiment

# Battery consumption

- Limited battery supply may hold back electrification
- Charging and discharging causes battery wear
- Vehicles on ERS can bypass the battery
- ~4000 km ERS on 6000 km road network reduces system battery consumption by 50%
- **Passenger cars** dominate battery consumption

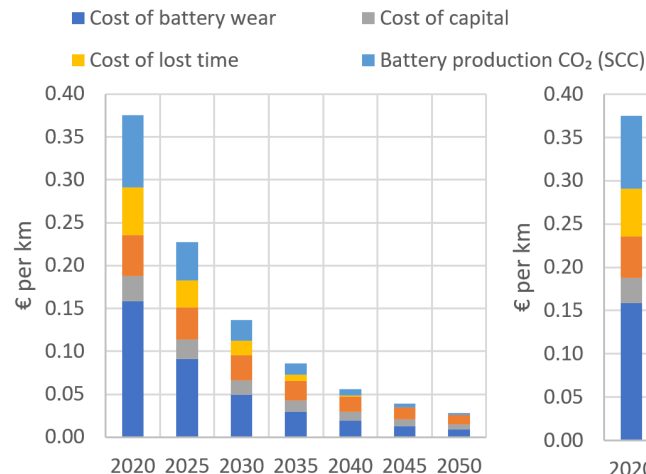


What if batteries do not get cheaper?

## Sensitivity Battery TCO

- Affected by many more parameters than cell price
- A trade-off between battery ageing, interest, cargo capacity and productive time
- Battery TCO will decrease, even if pack cost increases

If battery cell cost decreases

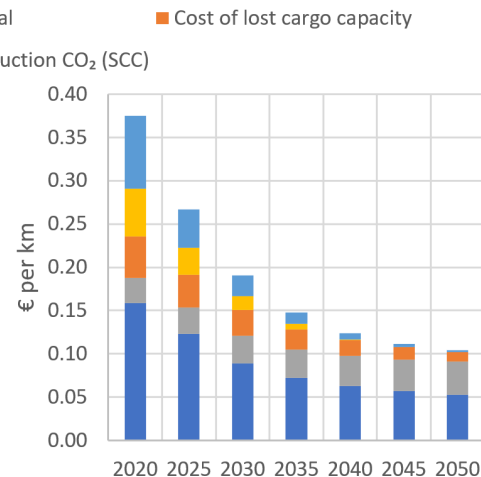


|      | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|------|------|------|------|------|------|------|------|
| 100  | 47   | 34   | 27   | 24   | 22   | 20   | 18   |
| 133  | 47   | 34   | 25   | 19   | 15   | 13   | 11   |
| 178  | 42   | 28   | 19   | 14   | 11   | 9    | 7    |
| 237  | 38   | 24   | 16   | 11   | 8    | 6    | 4    |
| 316  | 37   | 23   | 14   | 9    | 6    | 4    | 3    |
| 422  | 38   | 23   | 14   | 9    | 6    | 4    | 3    |
| 562  | 41   | 24   | 15   | 10   | 7    | 5    | 4    |
| 750  | 45   | 27   | 18   | 13   | 9    | 7    | 5    |
| 1000 | 53   | 33   | 22   | 16   | 12   | 9    | 6    |
| 1334 | 63   | 41   | 28   | 20   | 15   | 11   | 8    |

Minimum usable range [km]

€cent/km

If battery cell cost increases



|      | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|------|------|------|------|------|------|------|------|
| 100  | 47   | 37   | 31   | 28   | 26   | 23   | 21   |
| 133  | 47   | 37   | 29   | 23   | 19   | 17   | 15   |
| 178  | 42   | 31   | 23   | 18   | 15   | 13   | 11   |
| 237  | 38   | 28   | 20   | 15   | 13   | 11   | 10   |
| 316  | 37   | 26   | 19   | 15   | 12   | 10   | 9    |
| 422  | 38   | 27   | 19   | 15   | 13   | 12   | 11   |
| 562  | 41   | 29   | 21   | 18   | 16   | 15   | 14   |
| 750  | 45   | 33   | 26   | 22   | 20   | 19   | 18   |
| 1000 | 53   | 39   | 32   | 28   | 25   | 24   | 23   |
| 1334 | 63   | 48   | 40   | 35   | 33   | 31   | 30   |

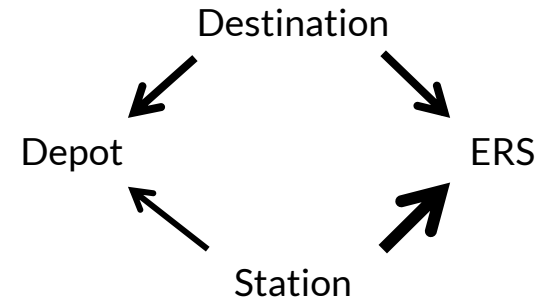
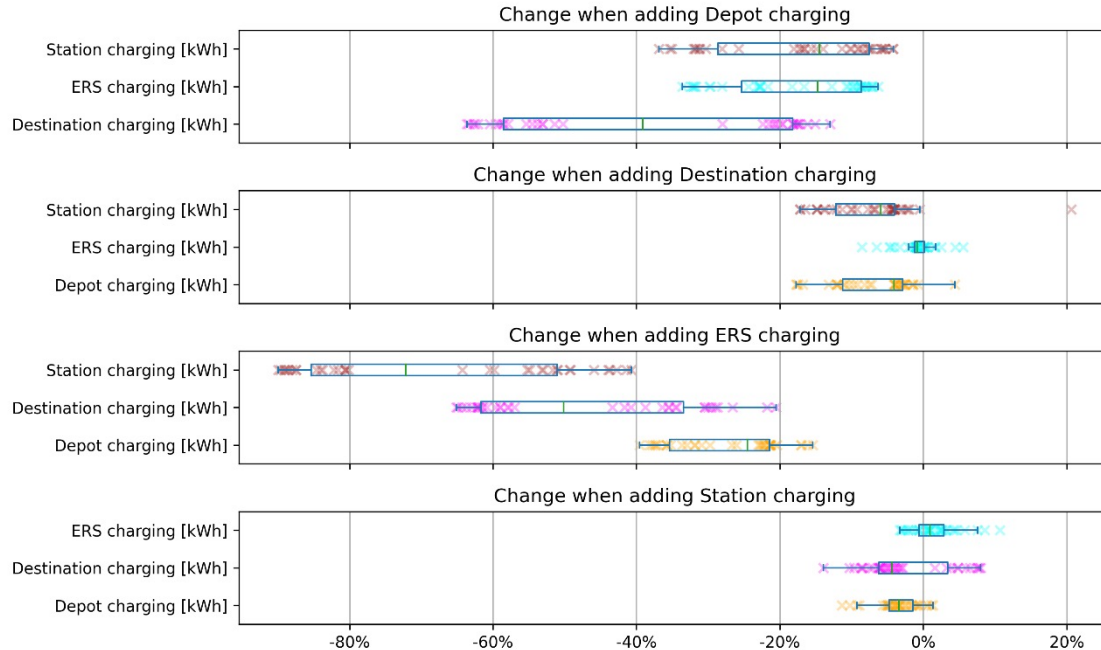
Minimum usable range [km]

€cent/km

How does ERS interact with other charging infrastructure?

## Experiment

# Change in kWh/year from A, when adding B

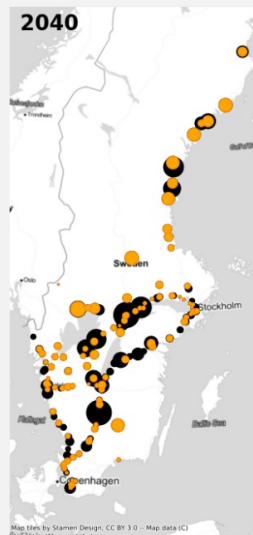
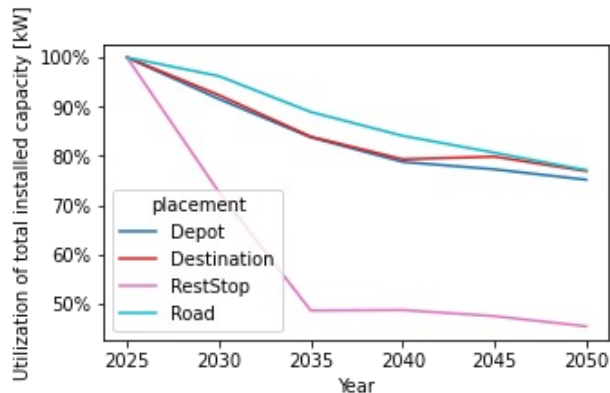




## Experiment

# Sensitivity to competition

Dense charging infrastructure →  
No demand for very large fast charging stations



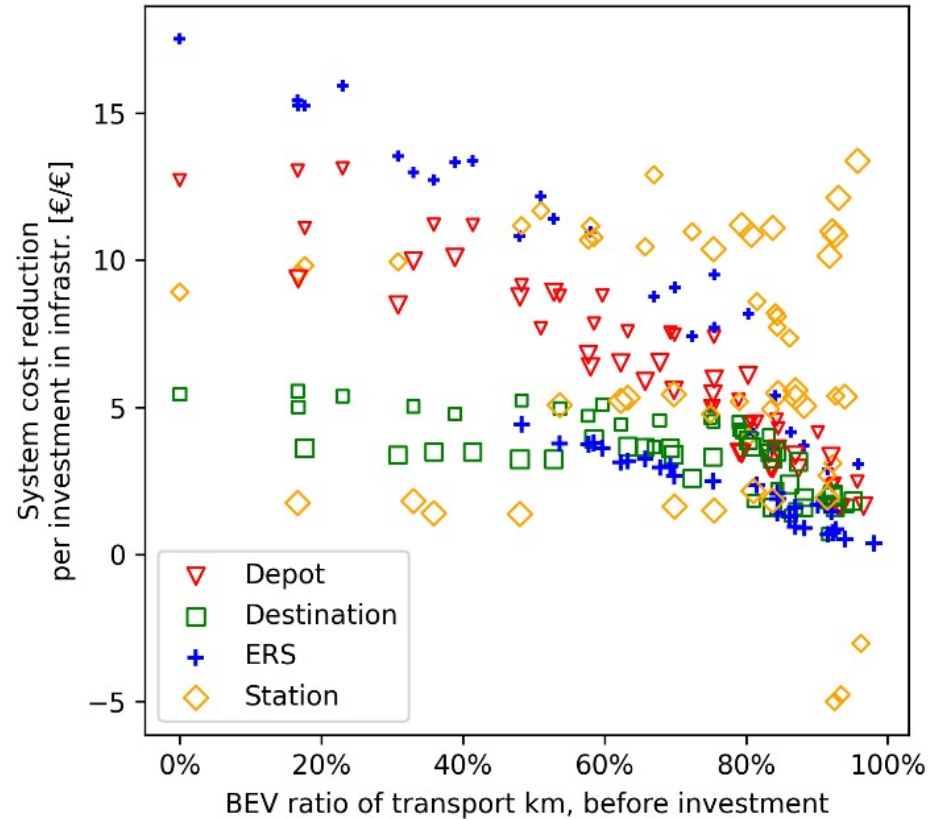
# System-Level Infrastructure ROI

## Early stages

Build ERS and depot charging

## Late stages

Build many small fast charging stations (away from ERS? at depots?)

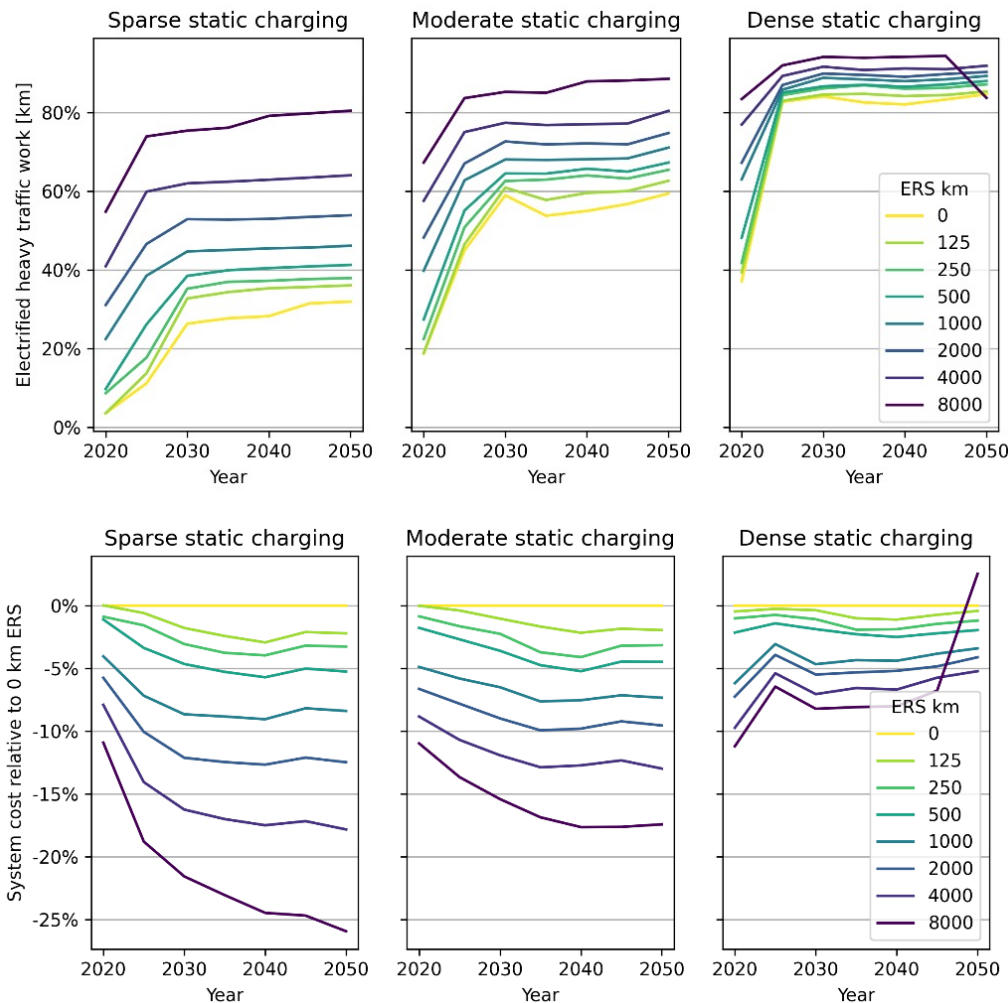


How does the marginal value of an ERS network change over its technical lifetime, with network size and with the density of other infrastructure?

## Experiment

# ERS network size

- Diminishing returns from more ERS, with denser charging infrastr. (any)
- Building more ERS still reduces system cost, up to a tipping point
- ERS on 3000 km road network in Sweden is not enough
- “Dense static charging” = 90% of depots, 90% of rest stops, 50% of destinations
- What infrastructure combination gets us to 90% BEV quickest?



What length, placement, buildout-rate, power and density maximizes ERS value?

## Experiment

# What ERS configuration is best?

## Method

- Scenarios grouped by availability of other charging infrastructure
- ERS configurations ranked within each group, by total system cost

## Result

- ERS decisions can be made without knowledge of future static charging infrastructure
- Aim for a large ERS network providing >150 kW per user (incl. gaps)
- Low-power ERS unfairly penalized by lack of light vehicle traffic in the model

|            | ERS config. rank | Sample size | Road ntwrk km | ERS infra. km (mean) | kW per vehicle | ERS density | Mean kW | Within-group rank |            |            | System bn€/y (mean) |
|------------|------------------|-------------|---------------|----------------------|----------------|-------------|---------|-------------------|------------|------------|---------------------|
|            |                  |             |               |                      |                |             |         | Mean              | 10th perc. | 90th perc. |                     |
| Equivalent | 1                | 27          | 6 000         | 2 027                | 700            | 50%         | 350     | 1.5               | 1          | 2.4        | 6.7                 |
|            | 2                | 27          | 6 000         | 1 079                | 700            | 25%         | 175     | 3.3               | 2          | 4          | 6.8                 |
|            | 3                | 27          | 6 000         | 3 822                | 700            | 100%        | 700     | 3.5               | 1          | 5          | 6.7                 |
|            | 4                | 27          | 6 000         | 4 072                | 300            | 100%        | 300     | 3.5               | 2          | 5          | 6.7                 |
|            | 5                | 27          | 6 000         | 2 077                | 300            | 50%         | 150     | 3.8               | 1.6        | 5          | 6.8                 |
|            | 6                | 27          | 2 000         | 1 601                | 700            | 100%        | 700     | 7.1               | 6          | 9.4        | 7.1                 |
|            | 7                | 27          | 2 000         | 1 622                | 300            | 100%        | 300     | 7.1               | 6          | 8          | 7.1                 |
|            | 8                | 27          | 2 000         | 815                  | 700            | 50%         | 350     | 7.7               | 7          | 9          | 7.1                 |
|            | 9                | 27          | 2 000         | 815                  | 300            | 50%         | 150     | 10.1              | 9          | 11         | 7.3                 |
|            | 10               | 27          | 2 000         | 433                  | 700            | 25%         | 175     | 10.3              | 9          | 12         | 7.3                 |
|            | 11               | 27          | 6 000         | 914                  | 300            | 25%         | 75      | 10.6              | 7.2        | 12         | 7.4                 |
|            | 12               | 27          | 6 000         | 3 062                | 100            | 100%        | 100     | 11.0              | 6.6        | 19         | 7.3                 |
|            | 13               | 27          | 2 000         | 373                  | 300            | 25%         | 75      | 13.5              | 12         | 14         | 7.7                 |
|            | 14               | 27          | 2 000         | 1 188                | 100            | 100%        | 100     | 13.7              | 13         | 17         | 7.6                 |
|            | 15               | 27          | 2 000         | 577                  | 100            | 50%         | 50      | 15.7              | 14.6       | 16         | 7.9                 |
|            | 16               | 27          | 6 000         | 1 502                | 100            | 50%         | 50      | 15.7              | 15         | 18         | 7.8                 |
|            | 17               | 27          | 6 000         | 594                  | 100            | 25%         | 25      | 16.7              | 14         | 19         | 8.0                 |
|            | 18               | 27          | 2 000         | 281                  | 100            | 25%         | 25      | 17.4              | 15         | 18         | 8.0                 |
|            | 19               | 27          | 0             | 0                    | 0              | 25%         | 0       | 17.7              | 14.2       | 19         | 8.1                 |

# Limitations

# Method Limitations

- Only heavy BEV and ICEV, no FCEV or PHEV
- No passenger cars or light trucks yet – greatly penalizes inductive ERS. Extra funding secured to include cars.
- No knowledge of actual depot and destination locations
- Route data correlates poorly with urban traffic
- Implicit assumption that charging infrastructure abroad is equivalent to national infrastructure
- Unclear how well the results generalize internationally
- Implicit assumption that routes are redistributed to best suited vehicles
- Battery ageing model is simpler than reality
- No interaction assumed with electricity or battery prices
- No interaction assumed between transport cost and traffic. Traffic assumed to remain at 2020 levels.
- No sensitivity analysis yet with regards to input parameters (except battery pack cost)
- No constraints to remove unrealistic scenarios



# Summary

## Summary

# Truck Electrification

- Lack of public charging infrastructure prevents electrification of heavy trucks today (battery tech is already good enough)
- Sweden's heavy-duty road transport is not a "hard-to-abate sector". Electrification reduces transport cost substantially. A rapid transition is possible.
- Battery TCO will decline, even if pack prices increase.
- Turbulence in the energy market increases the cost advantage for electric operation (see report)
- No alternative is cost competitive vs. electrification, including H<sub>2</sub>, biofuels and rail (see report)
- Transport OPEX after electrification is almost entirely driver. Very strong incentive for autonomous trucks, which would reduce time at depot and rest areas.

## Summary

# Charging Infrastructure

- ERS and depot charging give greatest ROI today
- >90% electrification possible without ERS, but very challenging. Transition likely much quicker with ERS.
- Large fast charging stations are quickly outcompeted, if ERS is built. Public sector clarity reduces private sector risk.
- Decisions about electric roads can be made independently of other charging infrastructure
- ERS reduce transport cost through approx. 70% reduced battery; hence used by 60–100% of heavy-duty traffic
- Under given assumptions, adding ERS is never a bad investment

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