System interaction effects between battery electric trucks (BETs), stationary charging and electric road systems (ERS)

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REGION BLEKINGE

Background

- Sweden to decrease GHG emissions from road traffic by 70% by 2030 vs. 2010

  20% achieved by 2019, mainly through biofuels

- Ratio of EVs of new registrations, in Sweden 2022:

  56% of passenger cars, 14% of light trucks, 3% of heavy trucks, 21% of buses

- Current approach to electric heavy trucks:
  large batteries + depot charging + fast charging stations

- Electric Road Systems () proposed

Research goal: Untangle interaction effects and capture system dynamics

- Substitution effects between static and dynamic charging
- Geographic network effects during build-out
- Changes in utilization when charging infrastructure gets denser and more vehicles are electric
- Infrastructure impact on vehicle batteries
- Impact of improved battery technology

Method

Methodological qualities

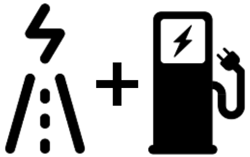
Four heavy truck classes share infrastructure

Millions of overlapping transport routes

Supply, demand and user charges in balance

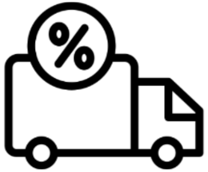
Lifecycle battery costs determined through use

Entire Swedish road network



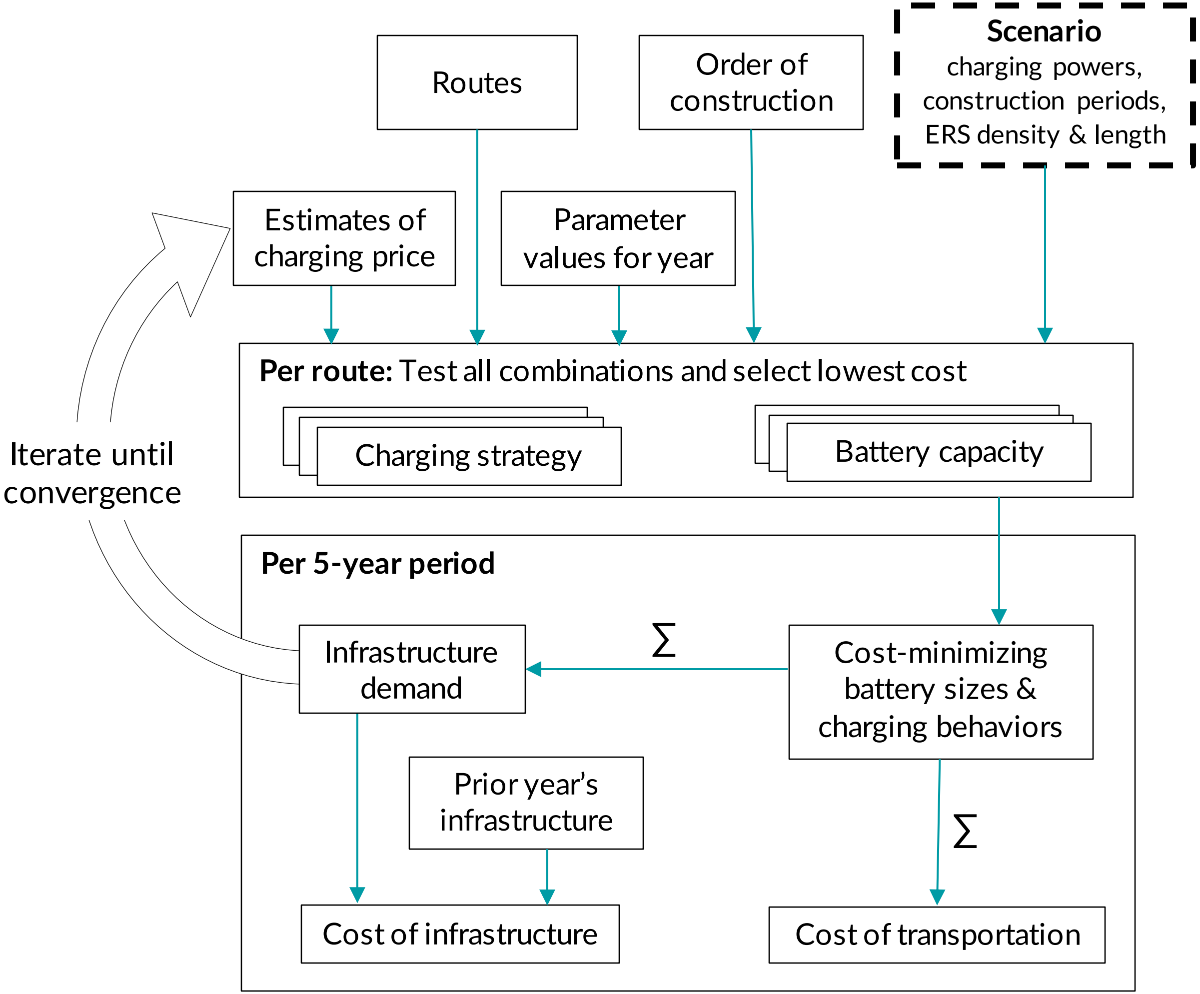
Combinations of static and dynamic charging

Competing charging infrastructure, built over time



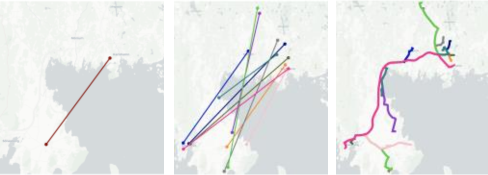
Tax revenue kept unchanged

Simulation model

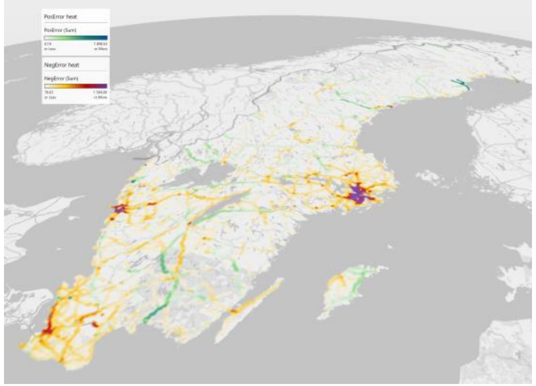


Traffic data:

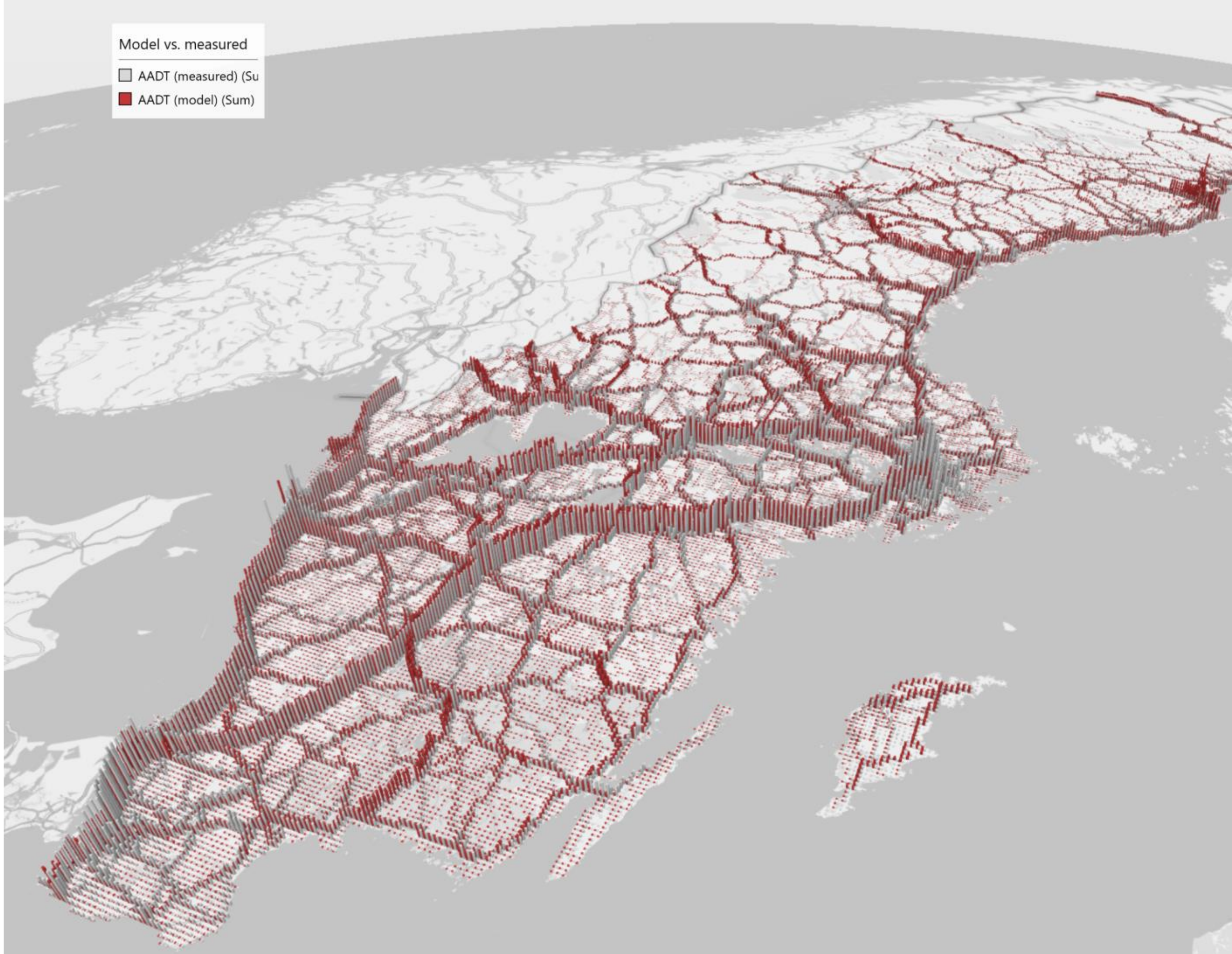
200k goods flows → 2M routes



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



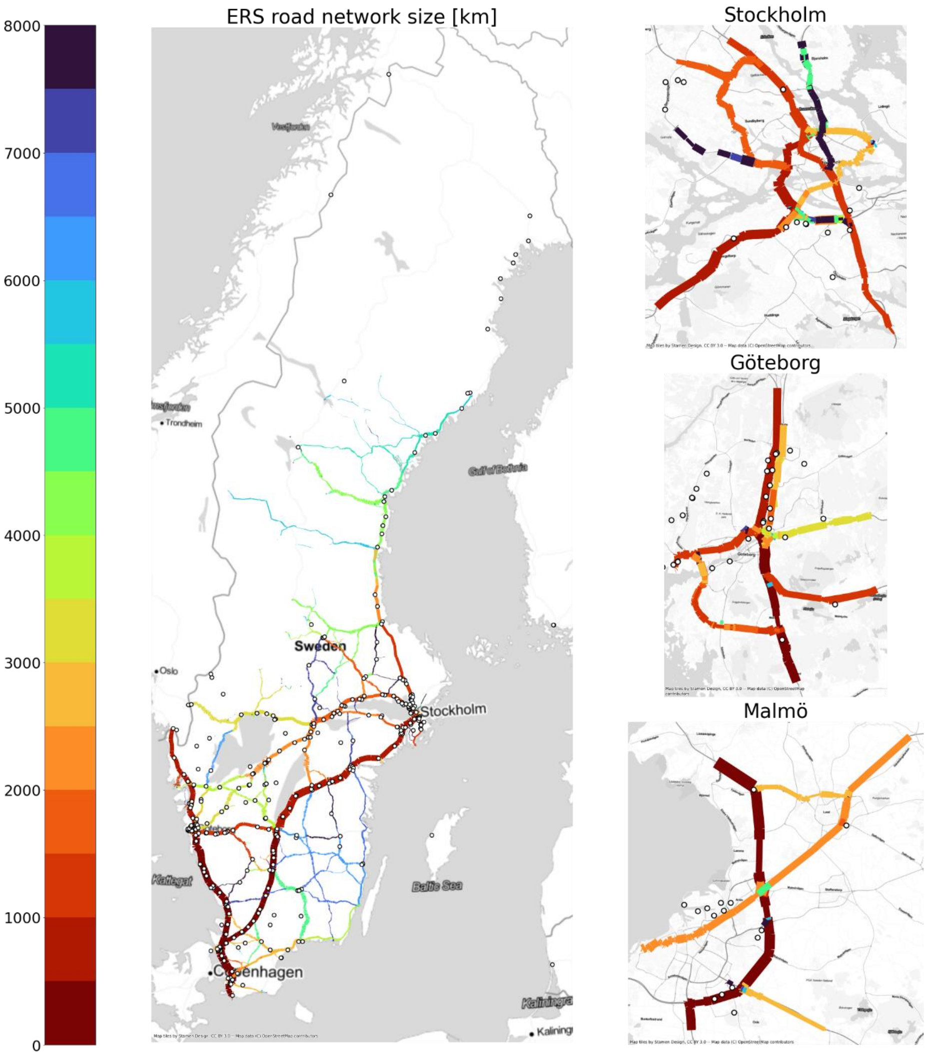
Underestimates (red) and overestimates (green) of traffic density on the road network. Underestimates may be due to lack of bus traffic.



Comparison after data calibration with measured AADT

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



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_2 sources = fossil and biofuels, Nordic energy mix, battery prod.

CO_2 = 0.7€/kg SCC, taxation 12% → 42% of SCC

Key Method Limitations

- Only heavy BEV and ICEV, no FCEV or PHEV
- No light traffic in simulation – penalizes low-power and urban ERS
- Route data correlates poorly with urban traffic
- Pop. density as proxy for depot and destination locations
- Implicit assumption that charging infrastructure abroad is equivalent to national infrastructure
- No interaction with traffic volume, electricity prices or battery prices

Results

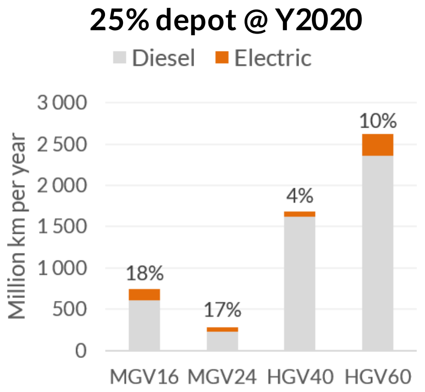
What range of results can this model output?

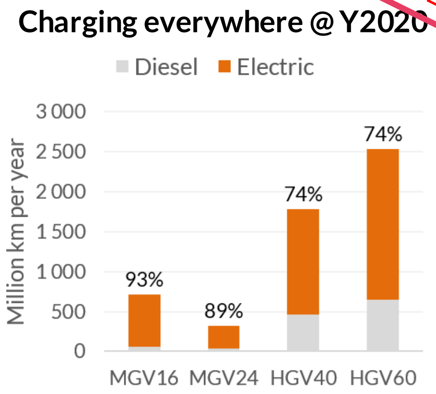
Can ERS generate socio-economic savings compared to electrification without ERS?

SUPPORT IN LITERATURE

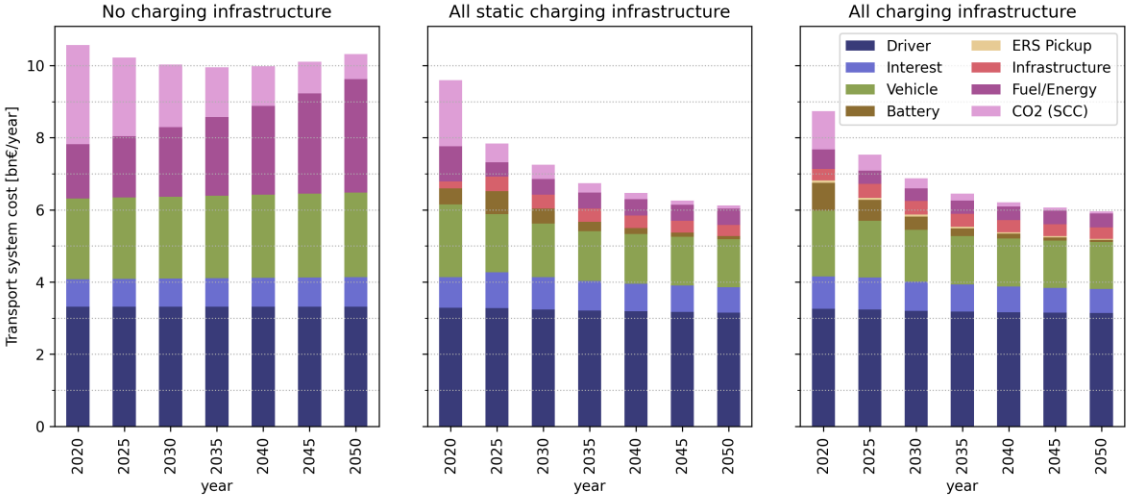
Experiment

Possible spread of system cost given model and input parameters





Annual system cost

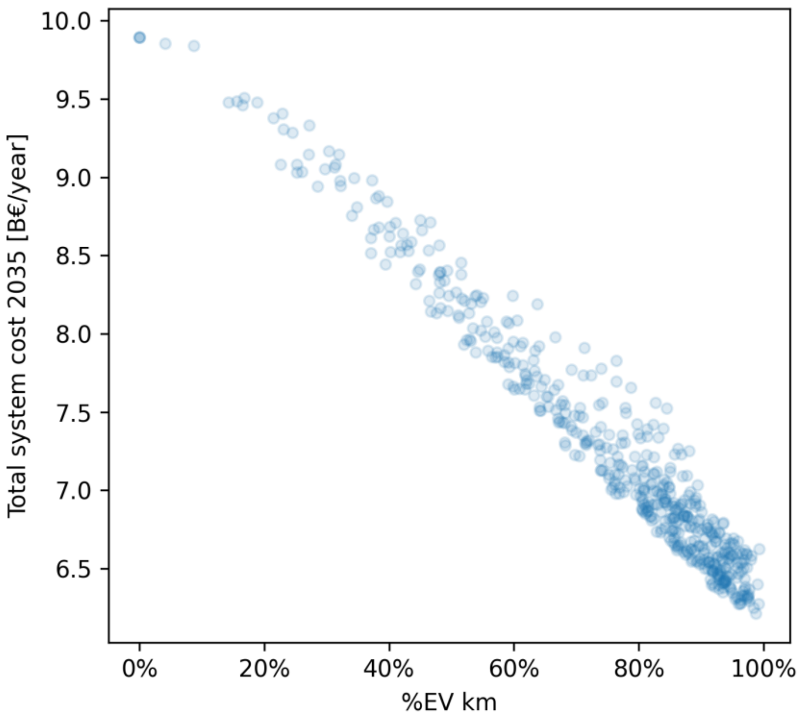


Driverless?

Experiment

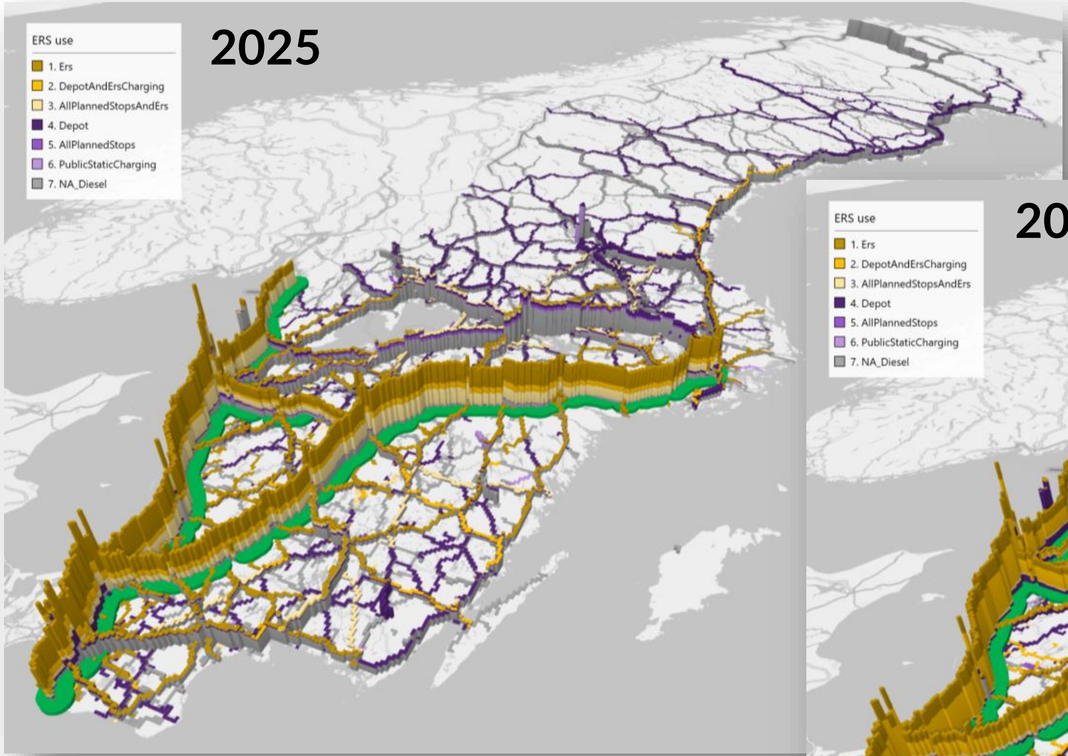
Electrification = cost reduction

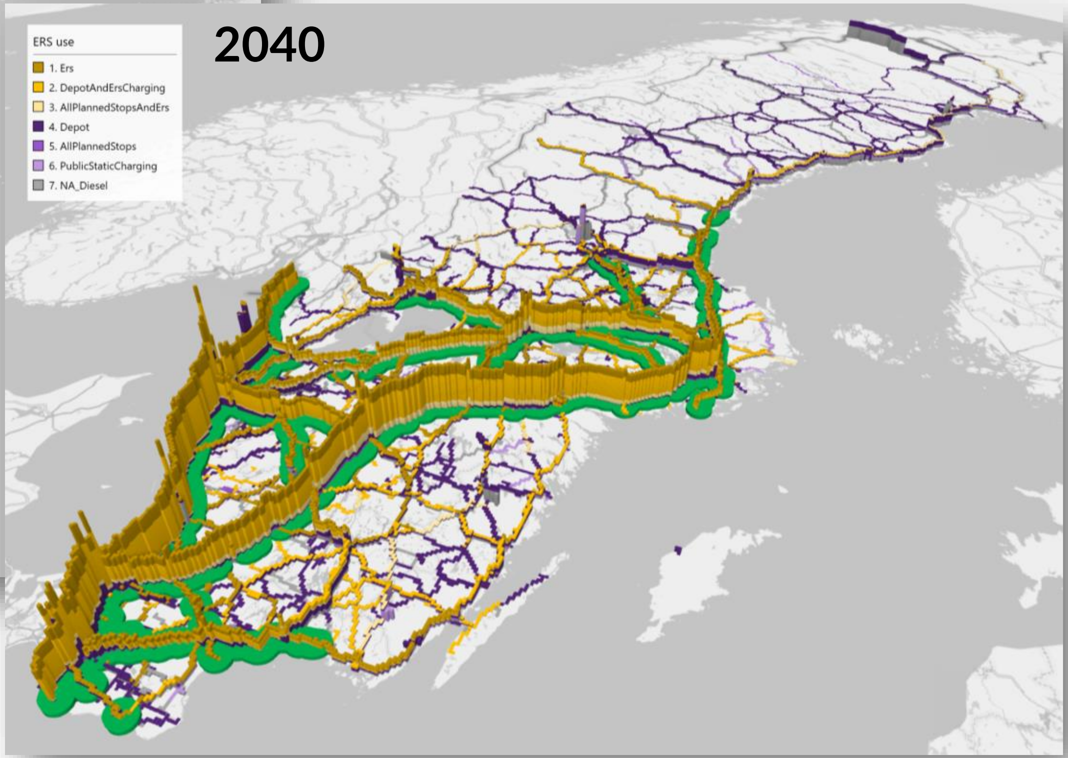
- 513 scenarios, year 2035, varied charging infrastructure
- System cost depends mostly on ratio of traffic electrified
- Several scenarios can minimize system cost, but many are unrealistic. Other qualities differ.



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

Almost all heavy traffic uses ERS where available





DISAGREES WITH OTHERS' ASSUMPTIONS

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

Experiment

Why is ERS attractive?

NOVEL CONTRIBUTION

- Access to ERS
  → smaller battery packs become viable
  → ~5% reduction of transport cost

- Contributions from:
  - Reduced capital interest cost
  - Reduced cost of battery calendar ageing
  - Lower weight, greater cargo capacity
  - More flexible stop locations

- Result is stable for all simulation years,
  despite changing cost and technology assumptions

Viable percent of routes (HGV40, 2030)

Charging strategy	150 kWh	250 kWh	450 kWh	700 kWh	1000 kWh
All static & ERS	37	60	83	92	94
Depot & ERS	33	53	71	82	86
All static	8	17	60	81	89
ERS only	18	32	44	48	51
Depot only	7	13	28	48	65
Stations and destination	1	3	7	13	17

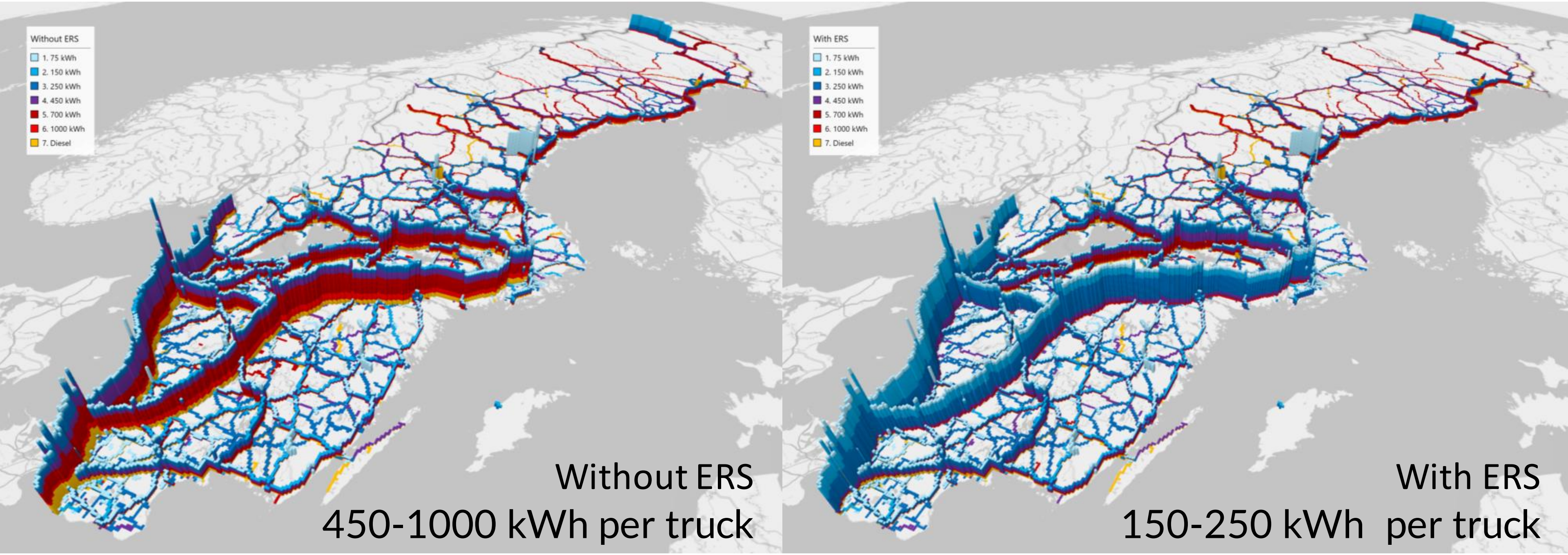
How does ERS affect sizing and ageing of battery packs in trucks?

RI.
SE

Experiment

Battery capacity per truck

STRONG SUPPORT
IN LITTERATURE,
INCL. FOR LIGHT TRAFFIC



NOVEL CONTRIBUTION

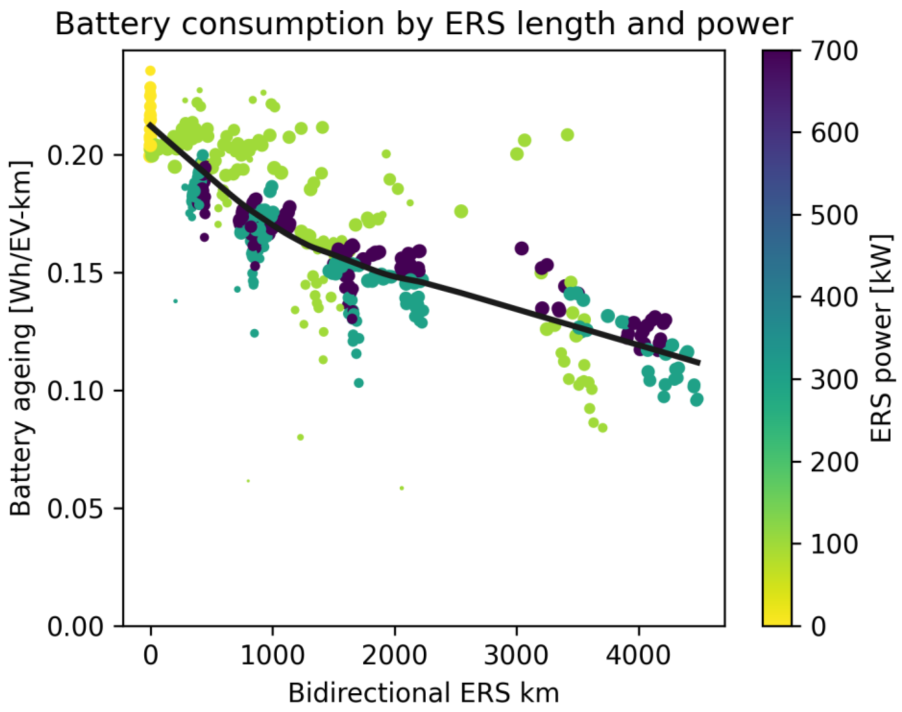
Experiment

ERS impact on total battery demand

- Total battery demand reduction driven by total length of ERS (not power)
- ~4000 km ERS reduces battery consumption by heavy trucks by 50%

Small batteries

1. don't reduce battery lifetime
2. lower cost of capital
3. lower cost of calendar ageing
4. fewer trips to move same cargo

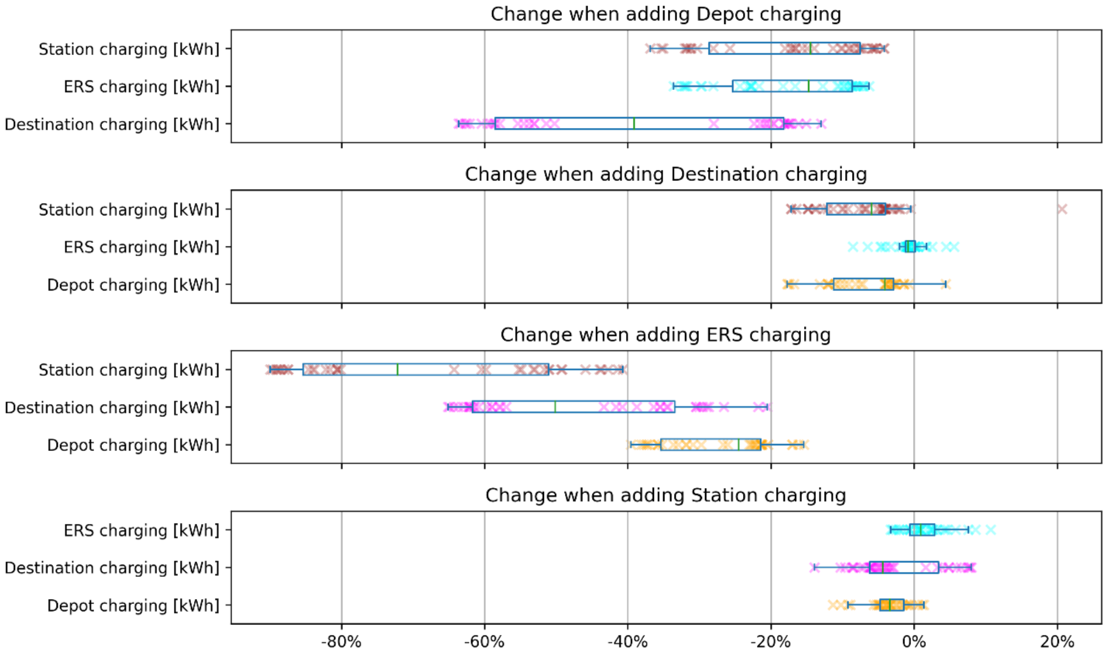


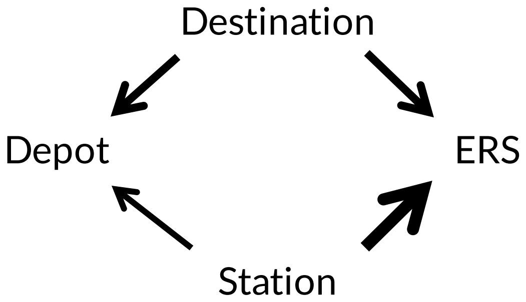
How does ERS interact with other charging infrastructure?

Experiment

Change in kWh/year from A, when adding B

NOVEL CONTRIBUTION



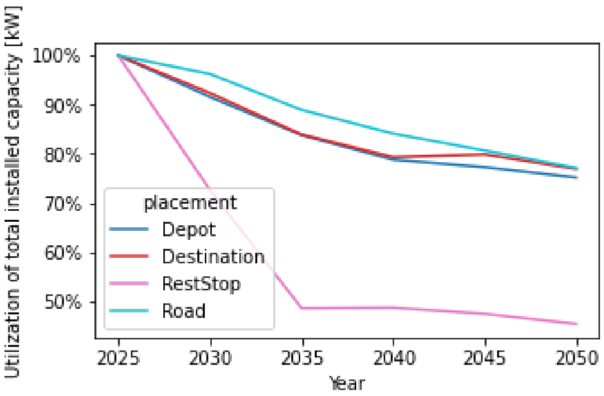


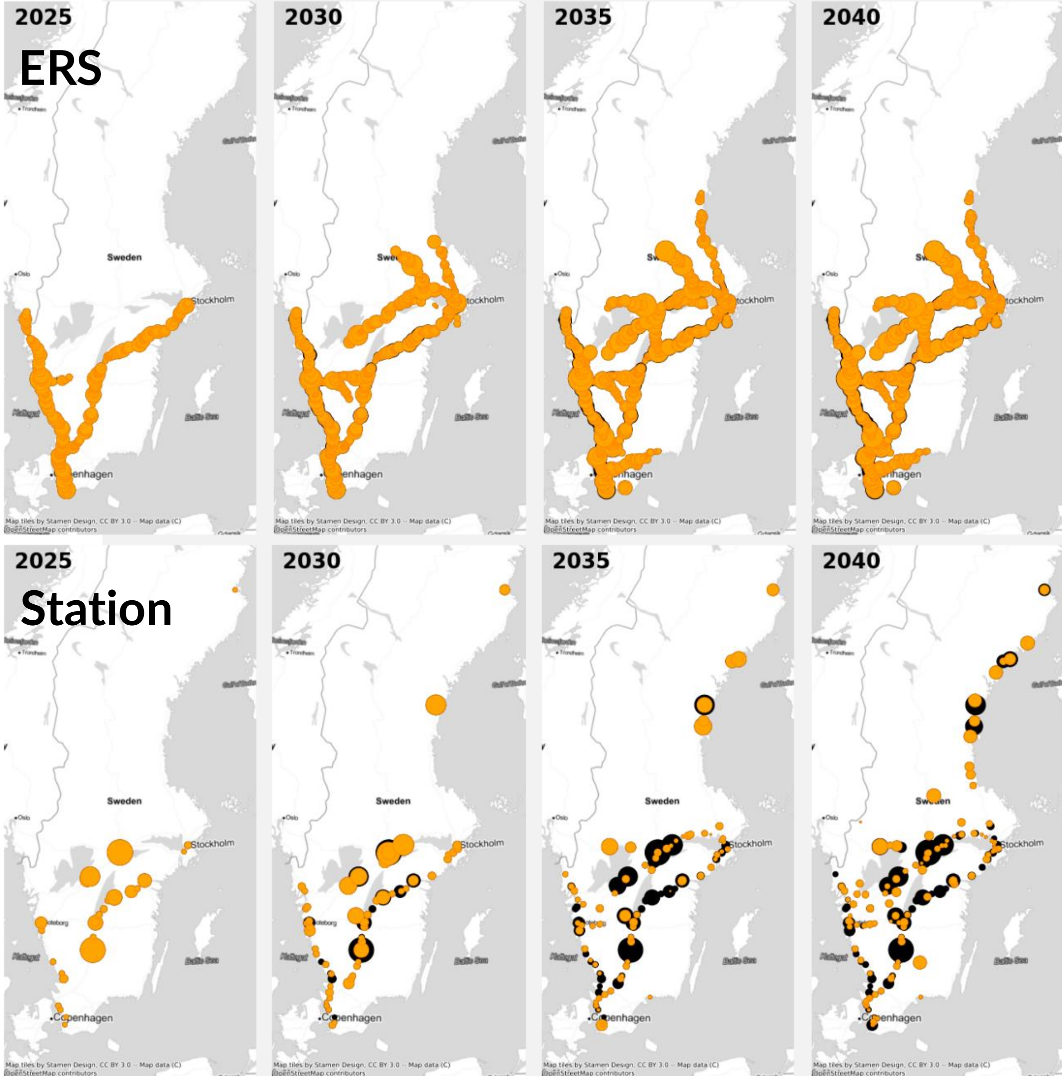
Experiment

Sensitivity to competition

NOVEL CONTRIBUTION

A growing ERS network outcompetes too large fast charging stations





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

NOVEL CONTRIBUTION

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: Mean	Within-group rank: 10th perc.	Within-group rank: 90th perc.	System bn€/y (mean)
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

Equivalent (ranks 1–5)

RI. SE

System-Level infrastructure ROI

Early stages

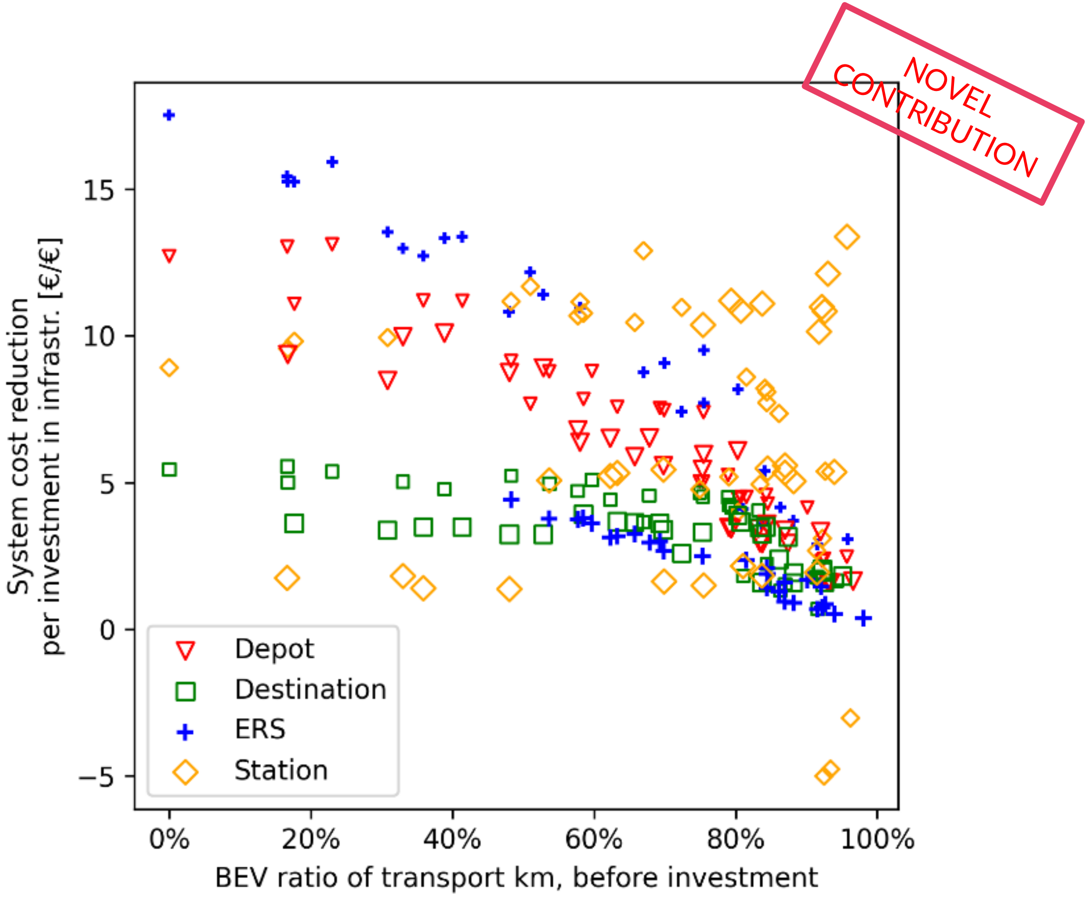
Build ERS and depot charging

Late stages

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

Inclusion of light traffic

Should boost ERS ROI

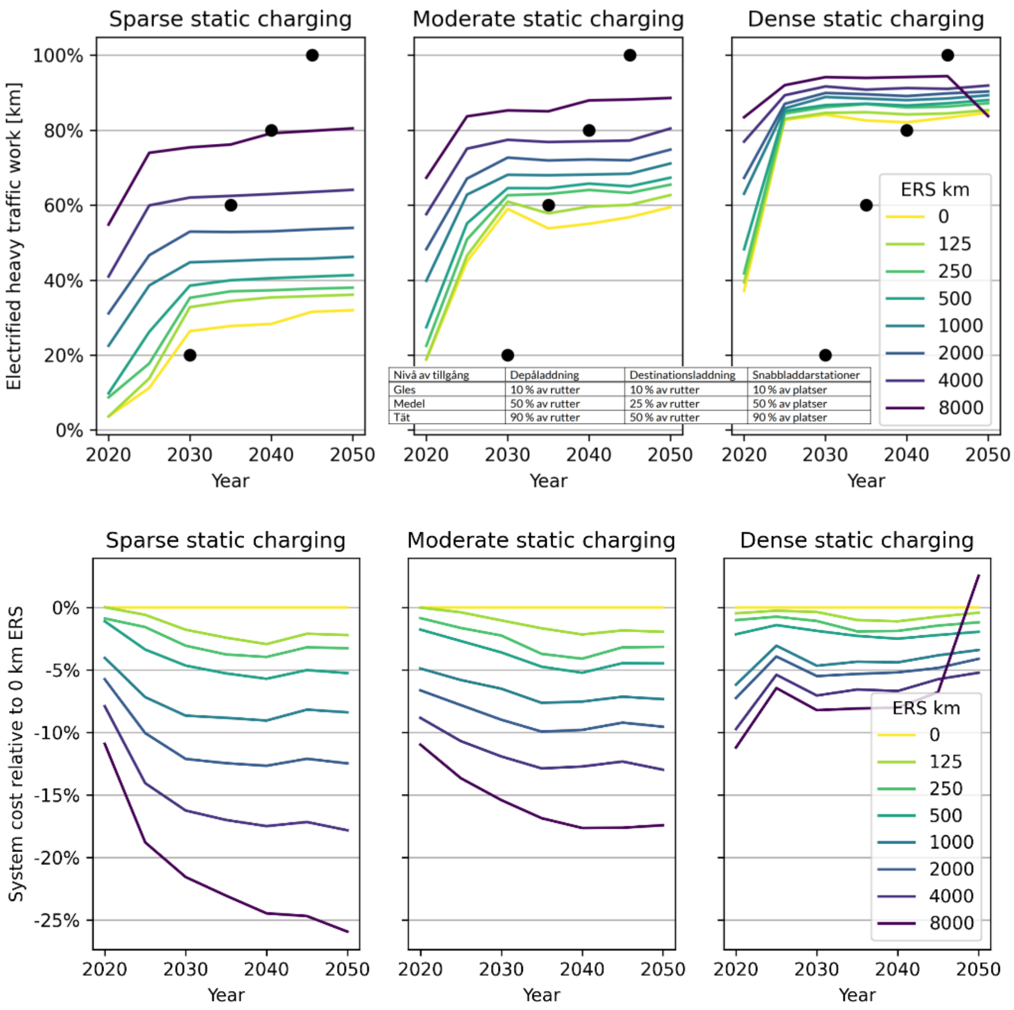


Small markers = none → some infrastructure
Large markers = some → much infrastructure

Experiment

ERS network size

- Static charging everywhere ≈ 85 % BETs (by when is >90% access at depot viable?)
- “Too much ERS” will not happen
- Adding ERS always reduces system cost
- 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?



Nivå av tillgång	Depåladdning	Destinationsladdning	Snabbladdarstationer
Gles	10 % av rutter	10 % av rutter	10 % av platser
Medel	50 % av rutter	25 % av rutter	50 % av platser
Tät	90 % av rutter	50 % av rutter	90 % av platser

Summary and implications

Static charging

- \+ Industry momentum
- \+ Mature standards
- \+ Incremental investment
- \+ Minor system change
- – Unproductive time
- – Inflexible stops, some only to charge
- – Large battery packs, more costly vehicles
- – Deep battery cycling
- – High c-rates
- – All energy via battery
- – Short(er) battery life

Dynamic charging

- – Pilot projects
- – Immature standards
- – Large upfront investment
- – Major system change
- \+ Productive time
- \+ Flexible stops, only logistical
- \+ Smaller battery packs, cheaper vehicles
- \+ Shallow battery cycling
- \+ Low(er) c-rates
- \+ Energy can bypass battery
- \+ Long(er) battery life

Summary and implications

1. Any dense public charging would make BETs the cheapest option – on most routes, today
   – infrastructure must enable 100% electric new vehicle sales ASAP

2. Rate of electrification is far more important than perfecting the charging infrastructure
   – does <u>also</u> building ERS enable faster electrification?

3. ERS allows 100% BETs with ~20-50% less batteries, and earlier TCO parity with diesel
   – will this accelerate the transition?
   – 80% of batteries in light vehicles → ERS for all traffic >> ERS for trucks

4. ERS would probably shift some power grid load to daytime, but also move load from local to regional grid
   – will this accelerate the transition?

5. All medium and heavy truck classes have cost incentives to use ERS, not only long-haul, but…

6. ERS in the charging mix only lowers BET transport cost by ~5%, vs. pure static charging
   – transport cost is dominated by driver and vehicle (excl. battery)
   – will driverless trucks (50% cost reduction) demand ERS?

7. The best decision is always to add >3000 km ERS with >150 kW/vehicle (incl. gaps)
   – are there even better solutions than those tested?

8. Difficult to reach >90% electrified traffic in Sweden without ERS. Is the model wrong?

9. Large fast charging stations are quickly outcompeted if ERS is built. Will it be?

Read the report

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Extra slides

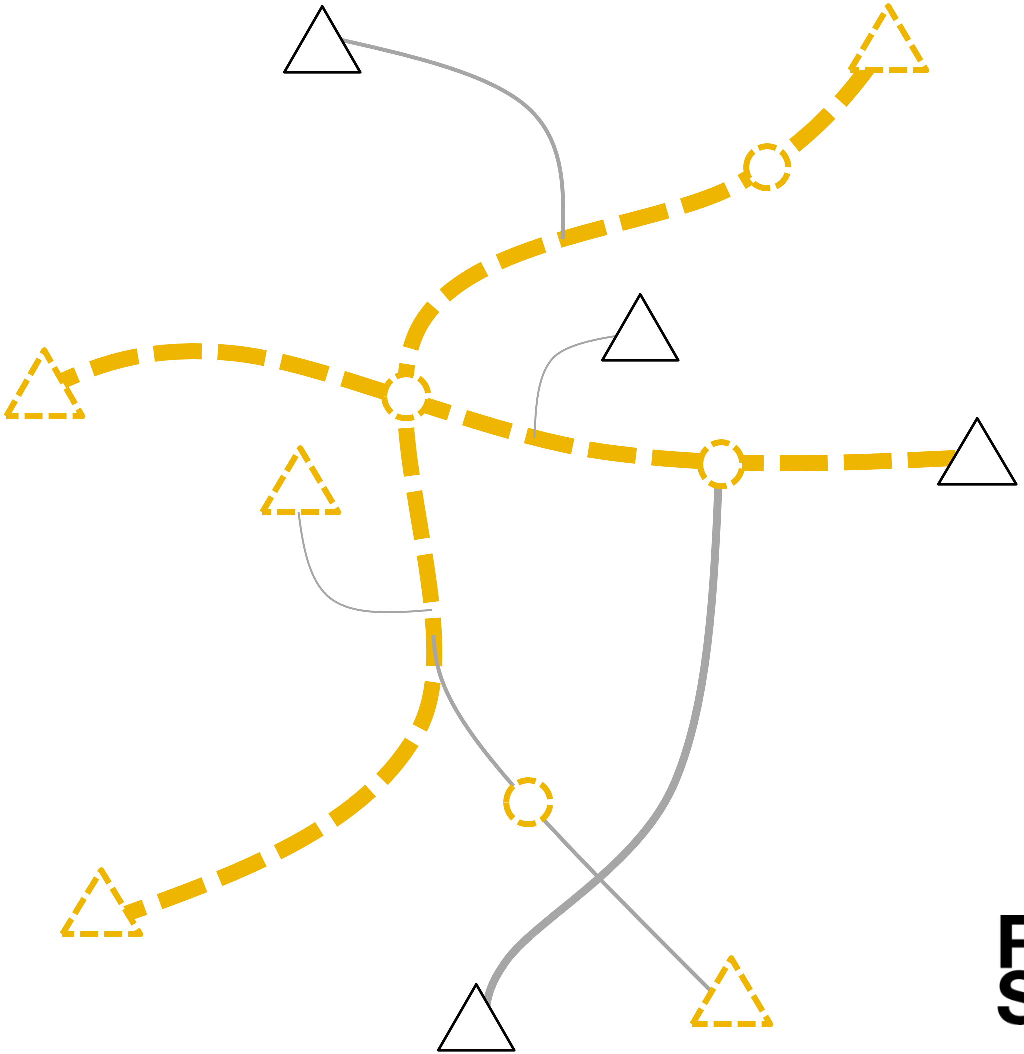
Simulation model

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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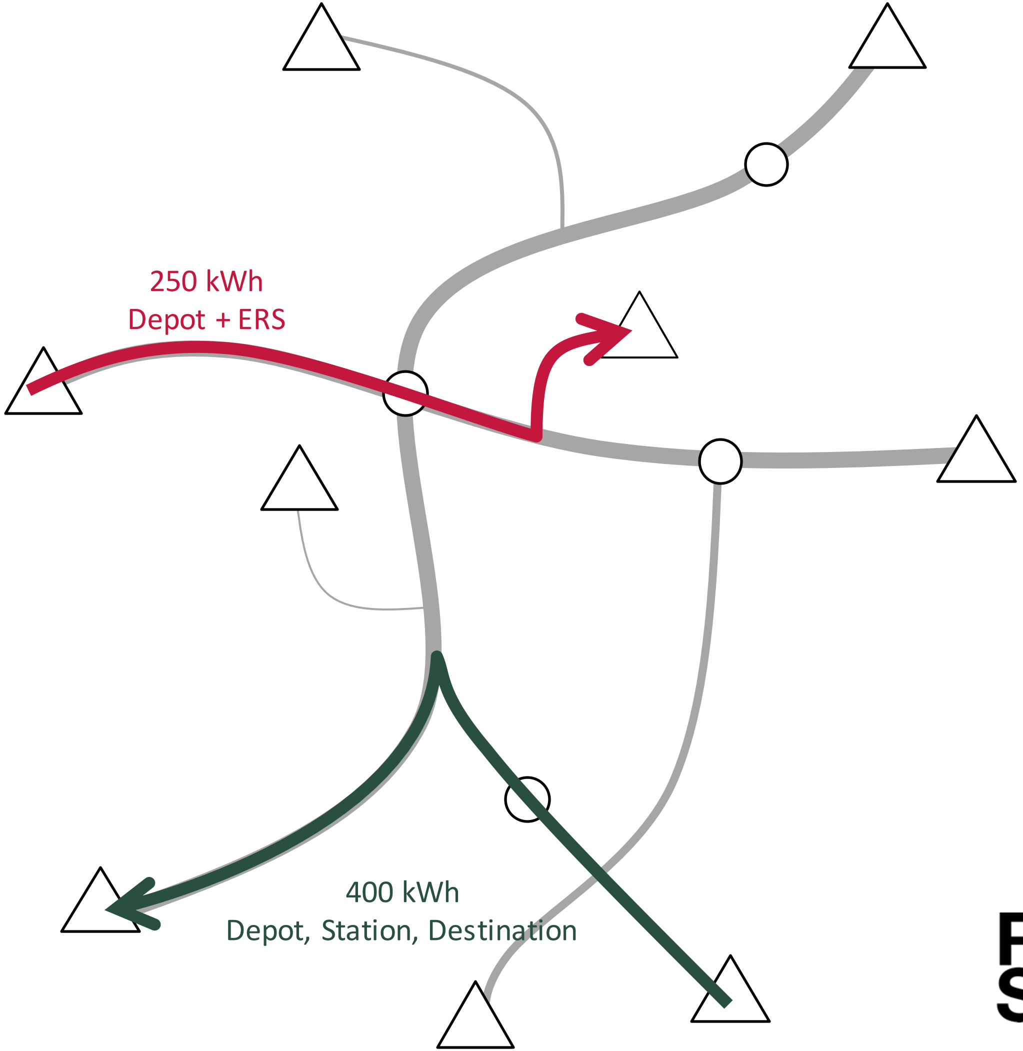

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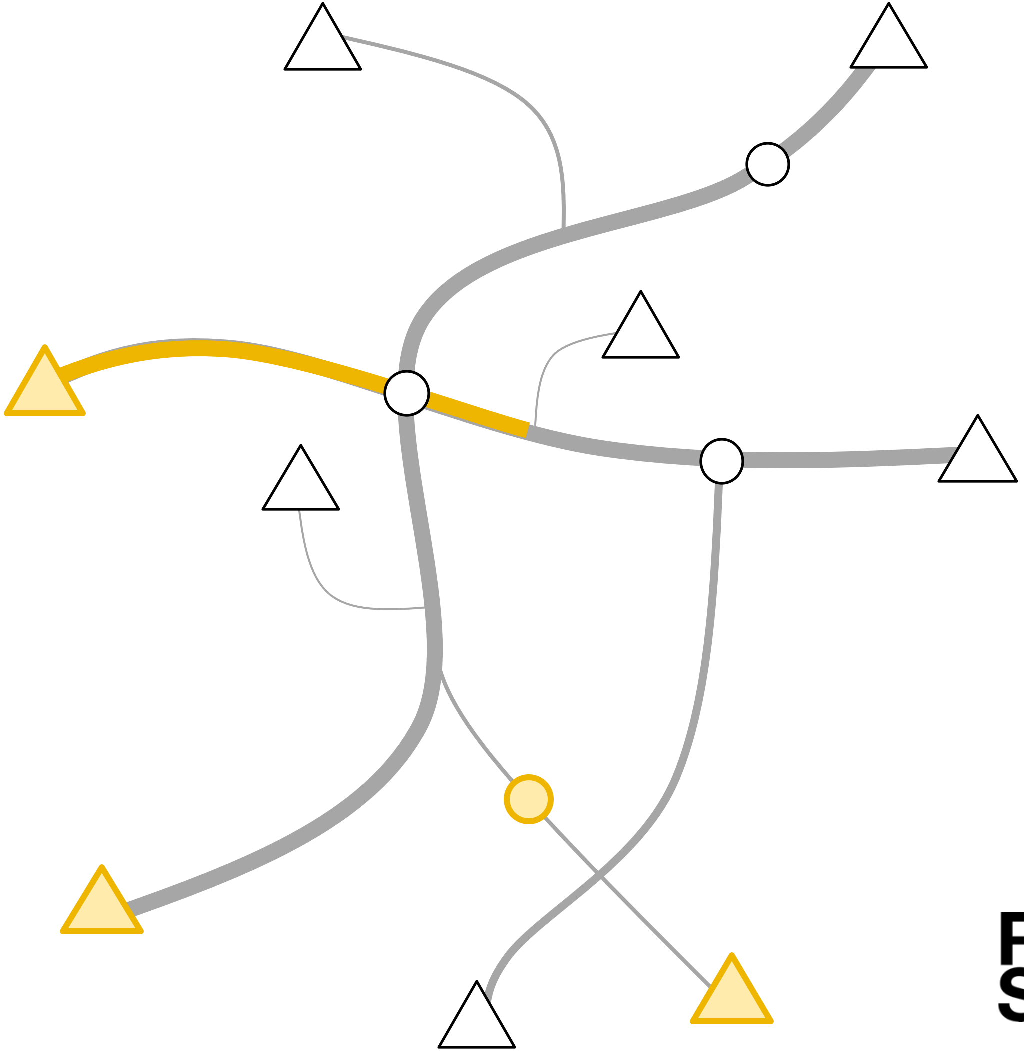
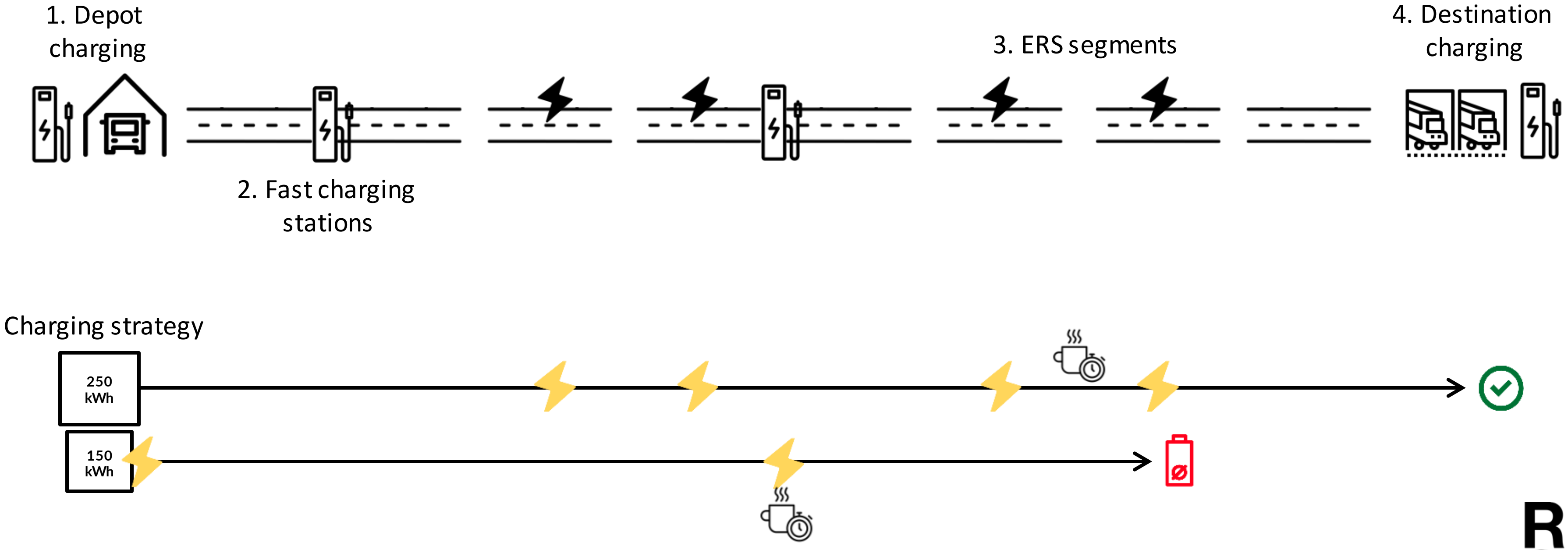


Four charging alternatives along routes



Levelized TCO decreases over time regardless of battery pack price