SCENARIO BASED ASSESSMENT OF HYDROGEN EMISSIONS FROM ROAD TRANSPORT REFUELLING INFRASTRUCTURE

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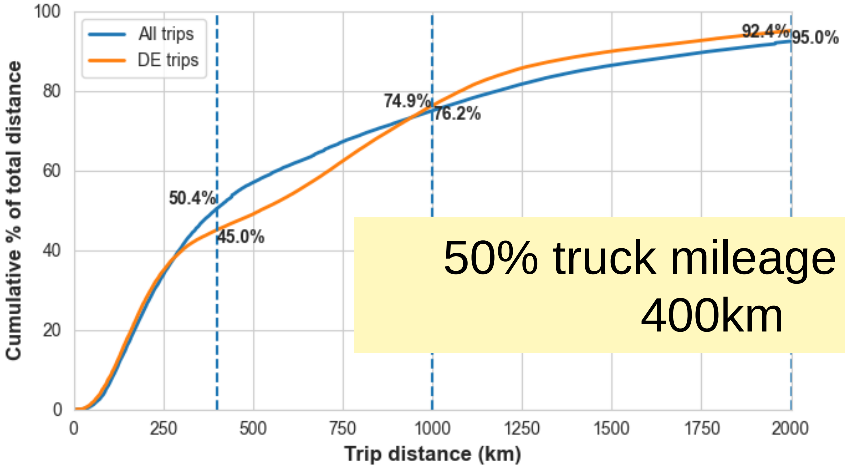
Cleanliest

Hydrogen emission inventories

Background

Freight truck trip length distribution



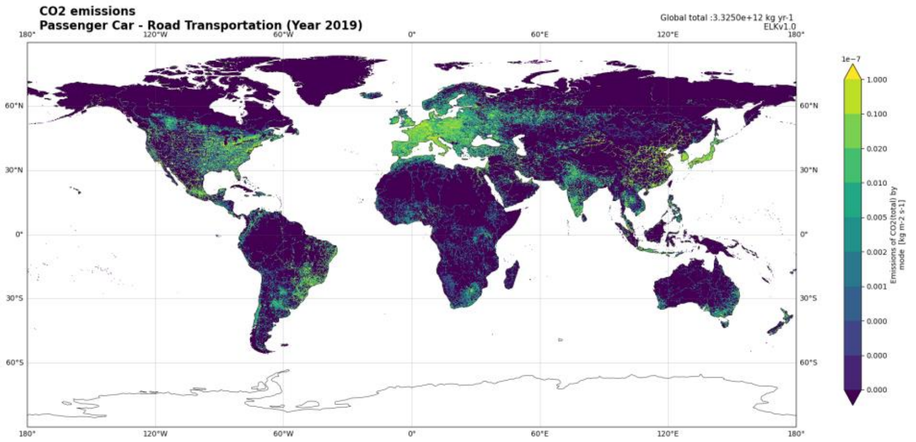
50% truck mileage above 400km

Source: Author, based on ETISplus[1] dataset

- Scenario based ramp-up up to 5-55% of FCEV penetration in worldwide HCV until year 2050
- Estimates of H2-Leakage from 1 – 10% by mass
- GWP estimates of 11.6 ± 2.8[2] in literature

Goal

Road transport emission inventory



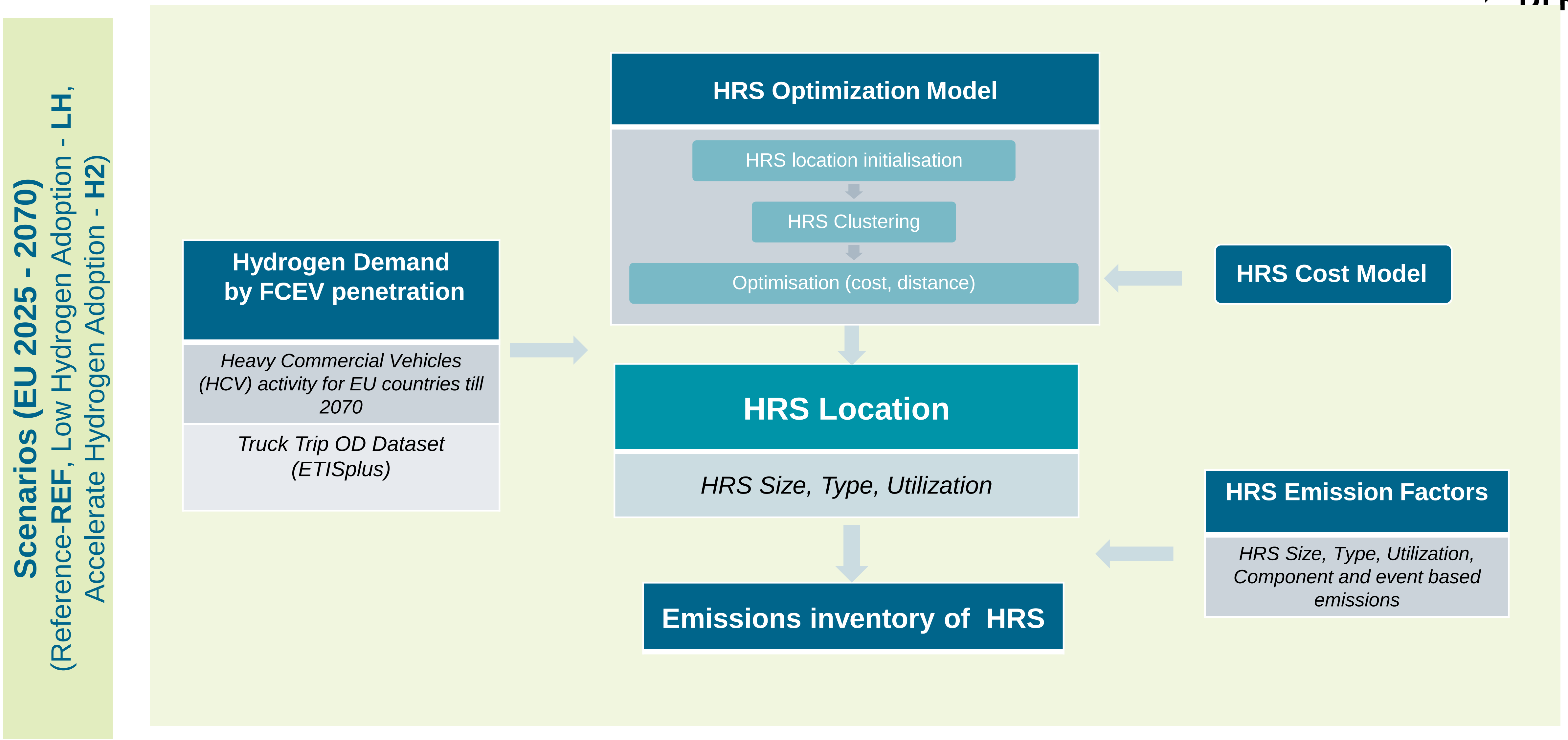
Source: Righi et al. (2026)[3]

- Opportunity and climate/cost benefit of hydrogen based scenarios and effects of scale
- Scenario based variation to understand sensitivities to hydrogen emissions by modelling climate impact

Source: Sand et al. (2023)[3]

DI0

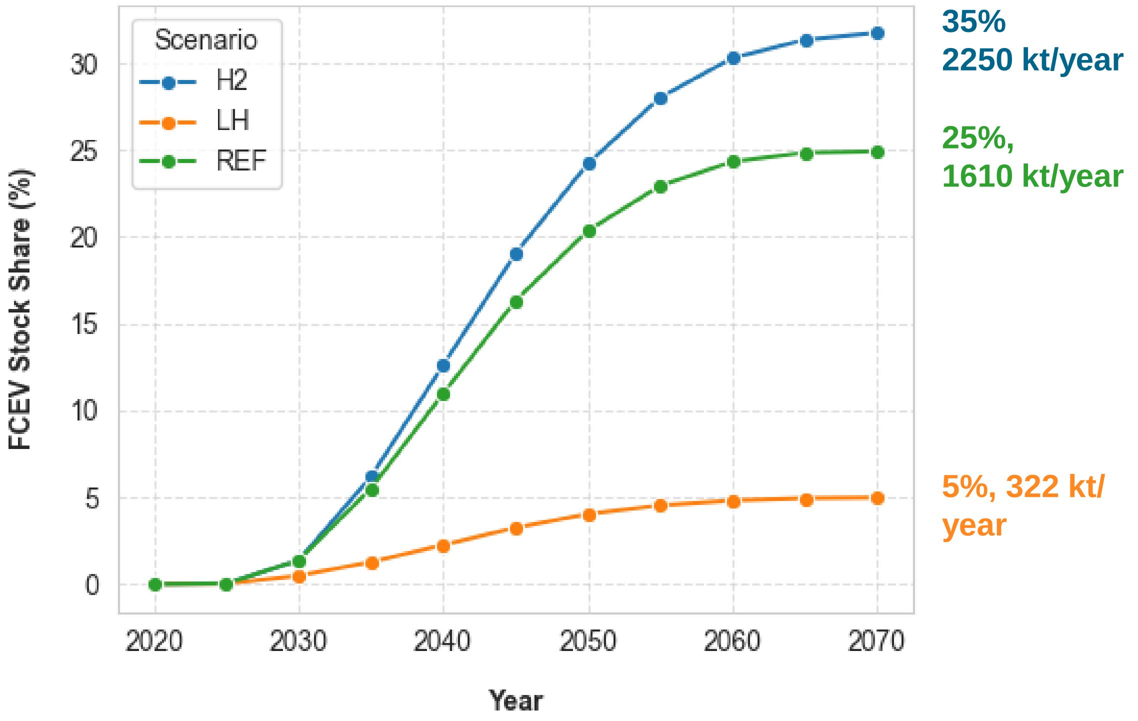
Methodology



HRS: Hydrogen Refueling Station

Hydrogen Demand : Heavy Commercial Vehicles (HCV)

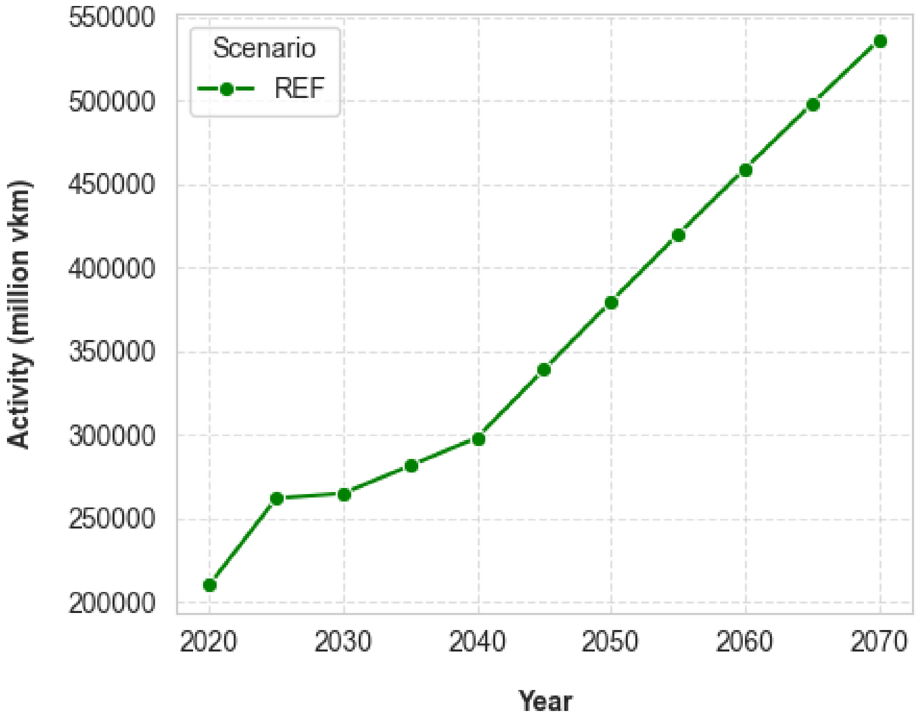
Heavy Freight road-transport, FCEV Penetration in fleet



Based on an EU new-registration model for HCV

DI0

Transport demand (vehicle-kilometres)



Data source: ITF Transport Outlook 2023[4] for OECD Europe region (own extrapolation beyond year 2050)

DI1

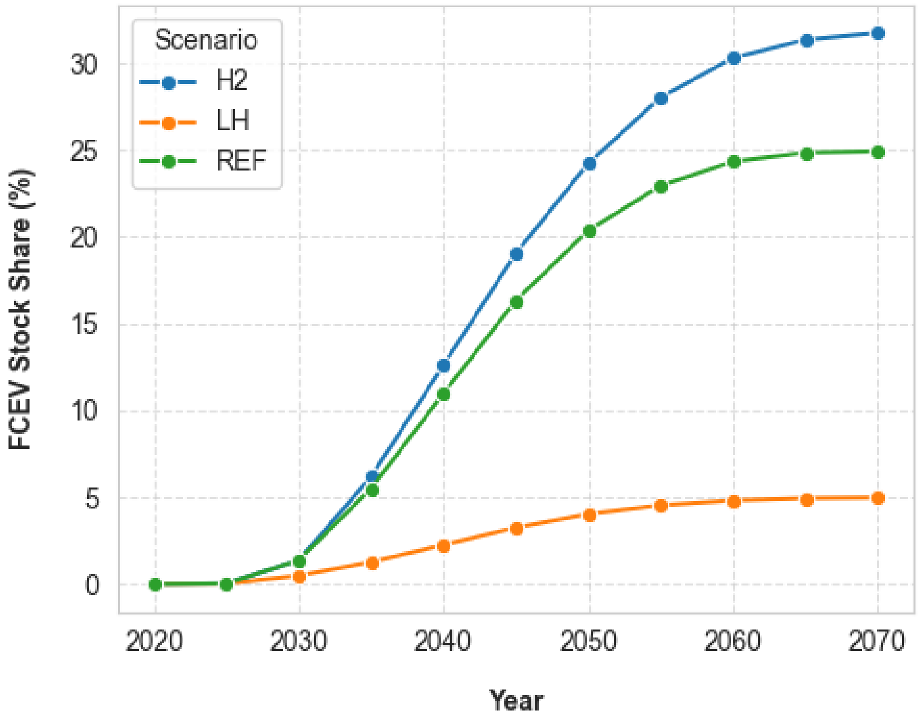
- Estimates for FCEV penetration for heavy commercial vehicle fleet is 5 - 35%

DI0

Hydrogen Demand (spatial) : Heavy Commercial Vehicles

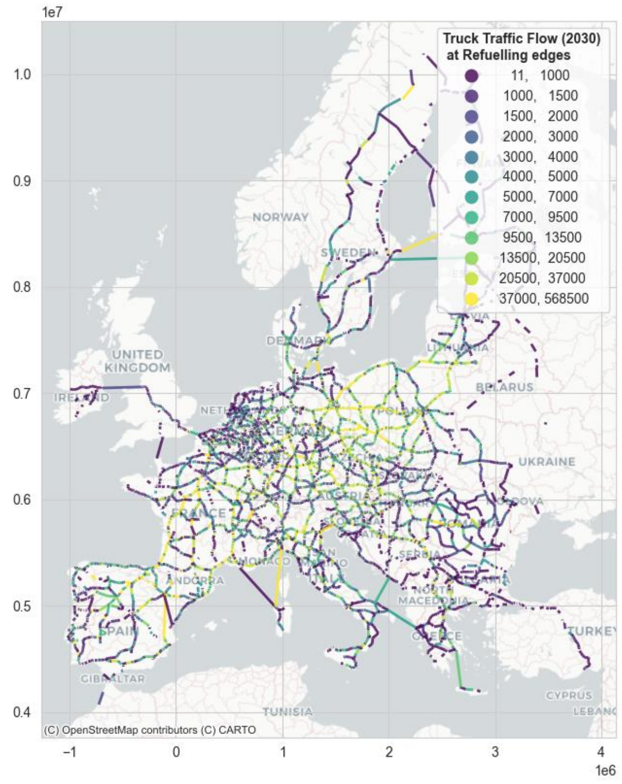
DLR

Heavy Freight road-transport, FCEV Penetration



FCEV penetration applied uniformly to ETISplus dataset for year to generate cumulative hydrogen demand by trips on road segments

Transport demand (Origin-Destination (OD) trips on TEN-T network)



- Hydrogen demand per road segment and scenario, based on dataset with 0.6 million OD trips
  What type of HRSs fulfill such large scale heterogenous demands?

HRS Pathways and Emission Factors

DLR

HRS Emission Sources

- **Hydrogen delivery** (affected by utilization rate of HRS and logistics)
- **Hydrogen storage** (affected by utilization rate of HRS and storage sizing)
- **Hydrogen processing** (affected by maintenance and process leaks)
- **Hydrogen dispensing** (number of refueling operations and thus utilization)

~ 1% leakage

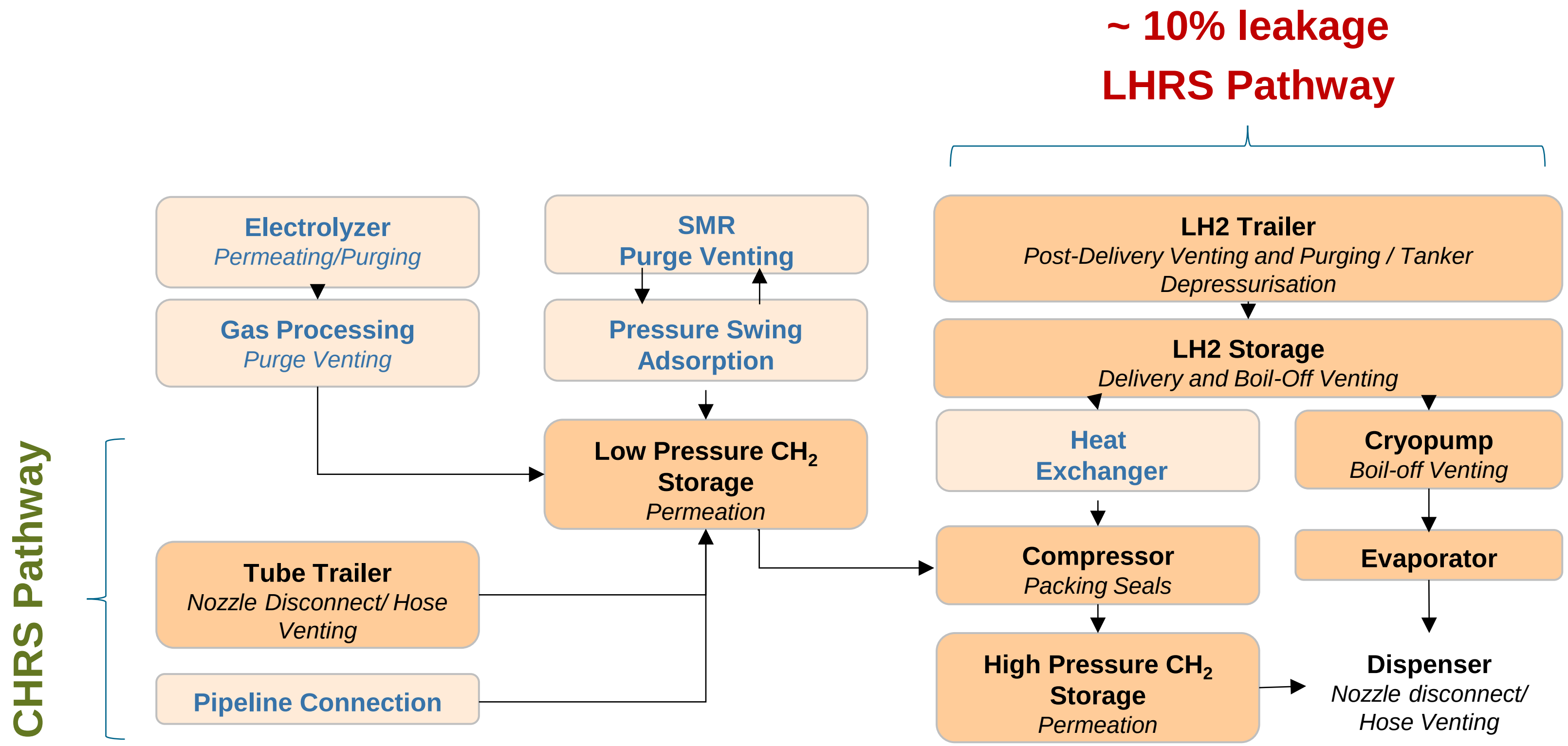
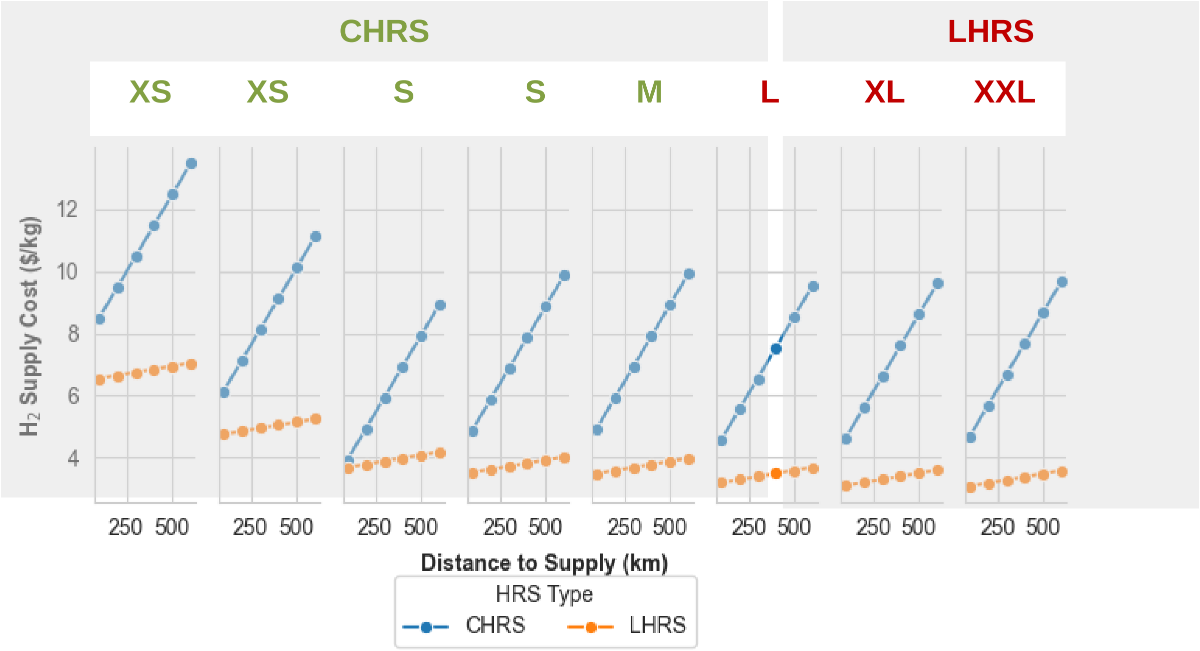


Figure adapted from Clark et al. (2025)[5], leakage estimates based on delivered hydrogen

- Highest emissions (hydrogen leakages) occur in LHRS pathway during delivery process, so why use it at all?

HRS Cost Model for compressed (CHRS) and liquefied hydrogen (LHRS)



*Based on low production scenario from **HDSAM**[7] model for heavy duty vehicles with tank capacity as 50 kg adapted for EU*

HRS Cost Breakdown and Pathway

LHRS costs = **Liquefier** + Terminal +Tractor-Trailer + Liquid Refueling Station

CHRS costs = GH2 Terminal + **Compressed H2 Truck-Tube** + Refueling Station

Influencing Supply Infrastructure

- Ports: EU ports[6] > 5 terminal
- Industrial Centres
- Pipeline: assumption of average distance of 200 km

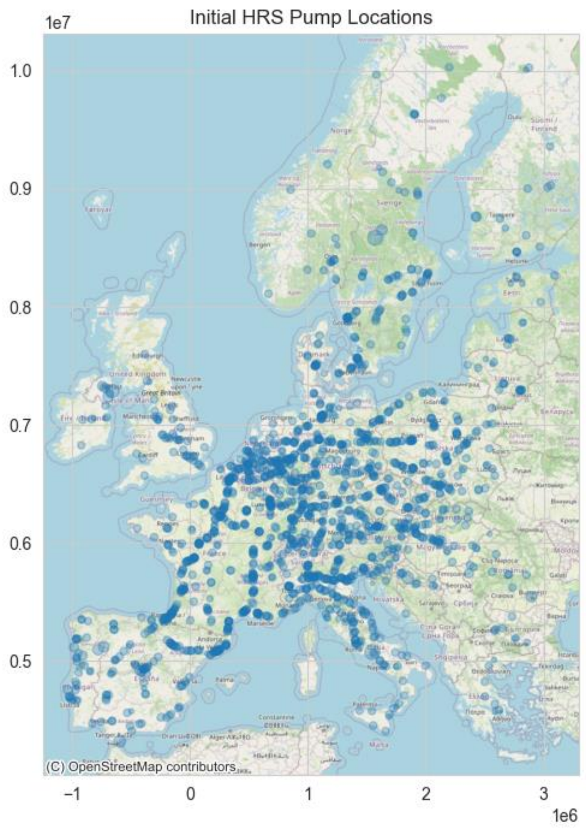
$$dist_{supply} = \min(dist_{port}, dist_{ic}, dist_{pipeline})$$

→ Because LHRSs get more cost effective for larger capacities (>L) and greater distances from supply

So how do we fulfill large scale demand with least supply cost and emission?

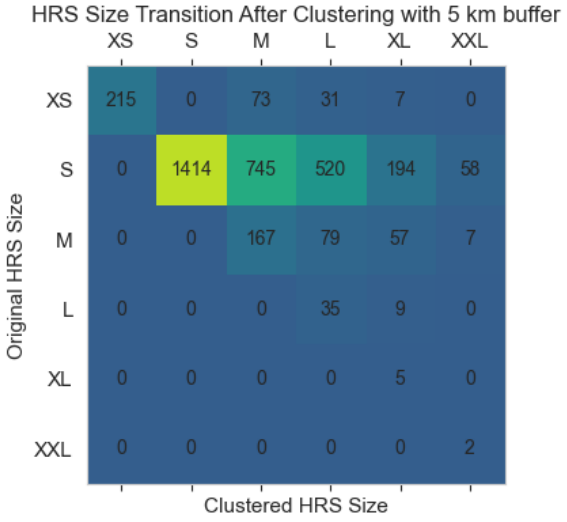
HRS Optimization Model

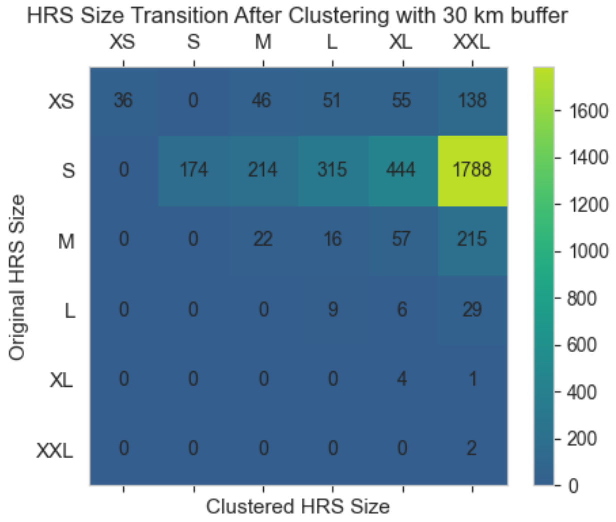
HRS Location Initialization



Based on Löfving et al. (2025)[8] NUTS3 level demand aggregation of ETISplus based demand and weighted distribution to parking spots by Speth et al (2021)[9]

HRS Clustering





Clustering Parameters

$\varepsilon_{distance}$ Clustering buffer radius used to aggregate HRS sizes

Clustering methodology

DBSCAN

- Potential to increase capacities of HRSs by clustering them and thus more cost effective LHRSs

HRS Optimization Model

Optimisation

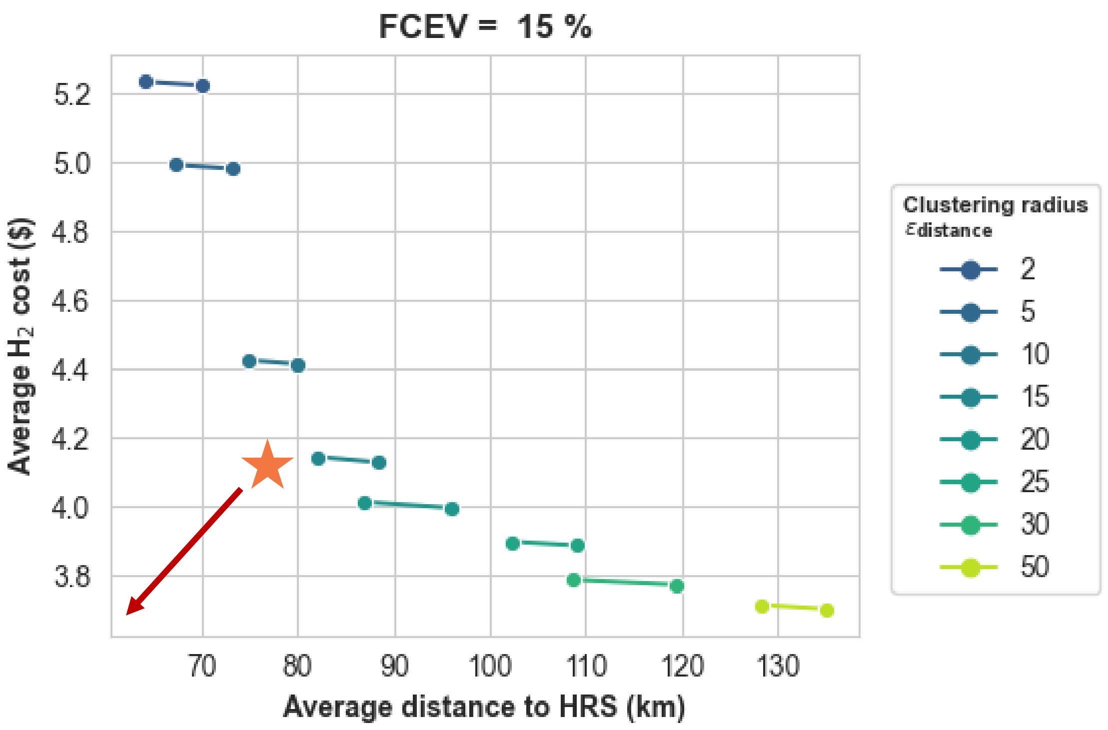
Objective Function

"Minimize cost of hydrogen refuelling when needed and minimize distance travelled to HRS from set of clustered HRS sites with a penalty to unmet demand"

Parameters and Sensitivity

- $\varepsilon_{distance}$ Clustering radius — **2 - 30 km**
- $\boldsymbol{\lambda_{dist}}$ **:** Cost to extra travel to HRS per distance unit — **0 - 0.4 €/km**
- $\boldsymbol{penalty}$ **:** Cost to Unfulfilled demand of hydrogen — fixed

Optimisation Results for EU OD trips

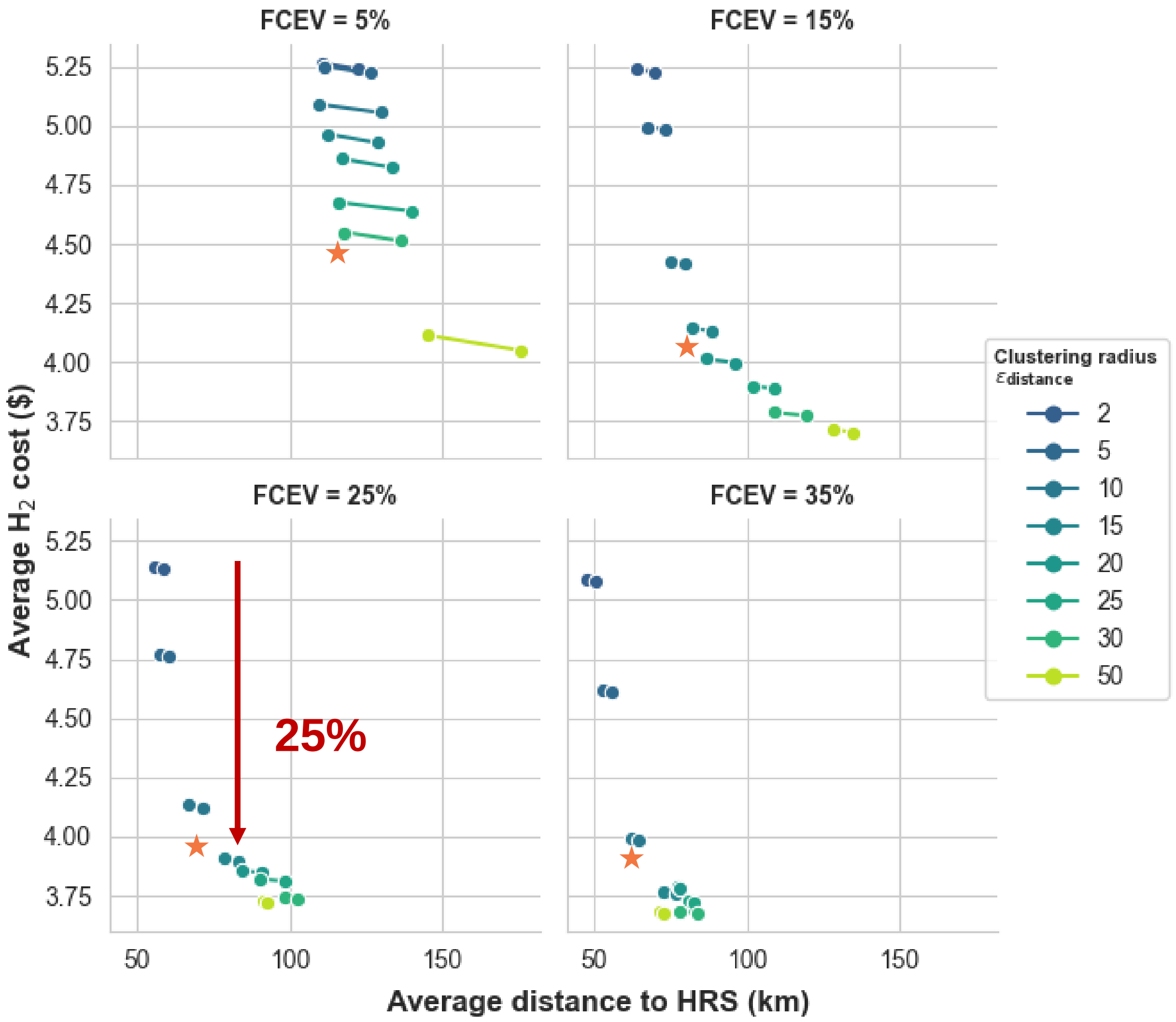


HRS Optimization Model

Optimisation Results

2050 Hydrogen Demand

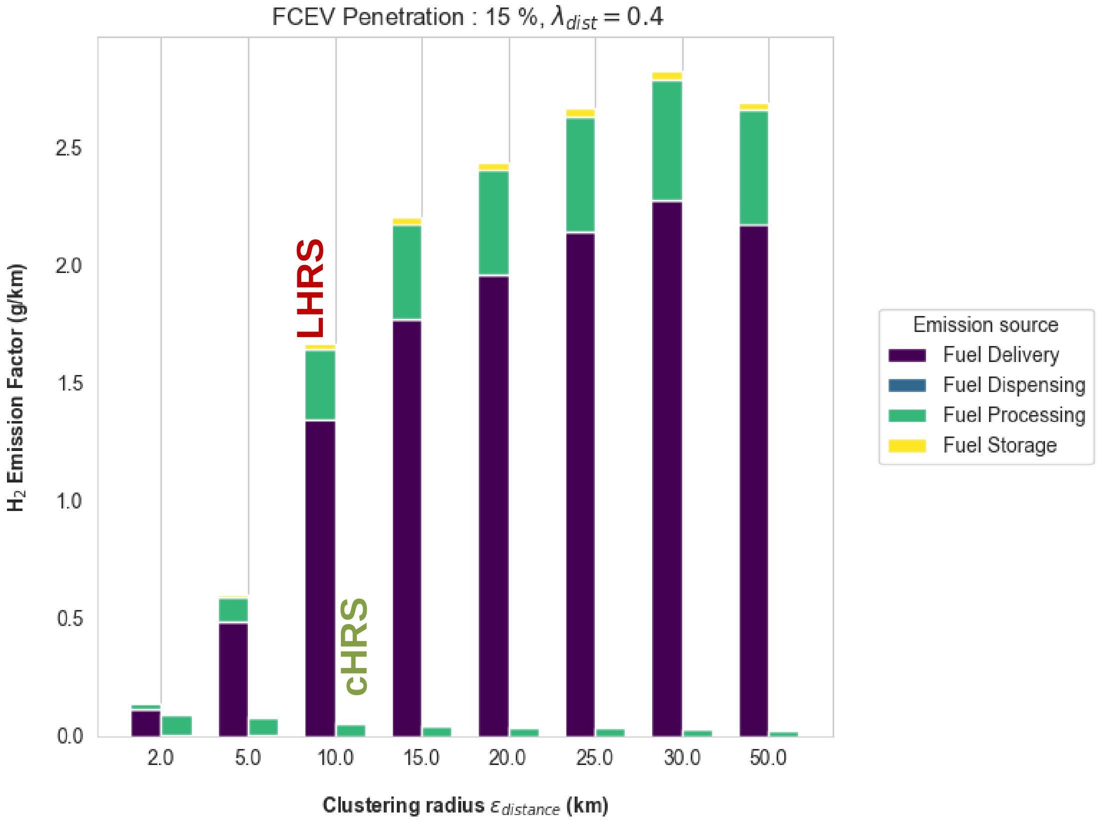
★ With increasing penetration of FCEV, optimum clustering of HRS leads to lower average hydrogen costs and lower distance to nearby HRS



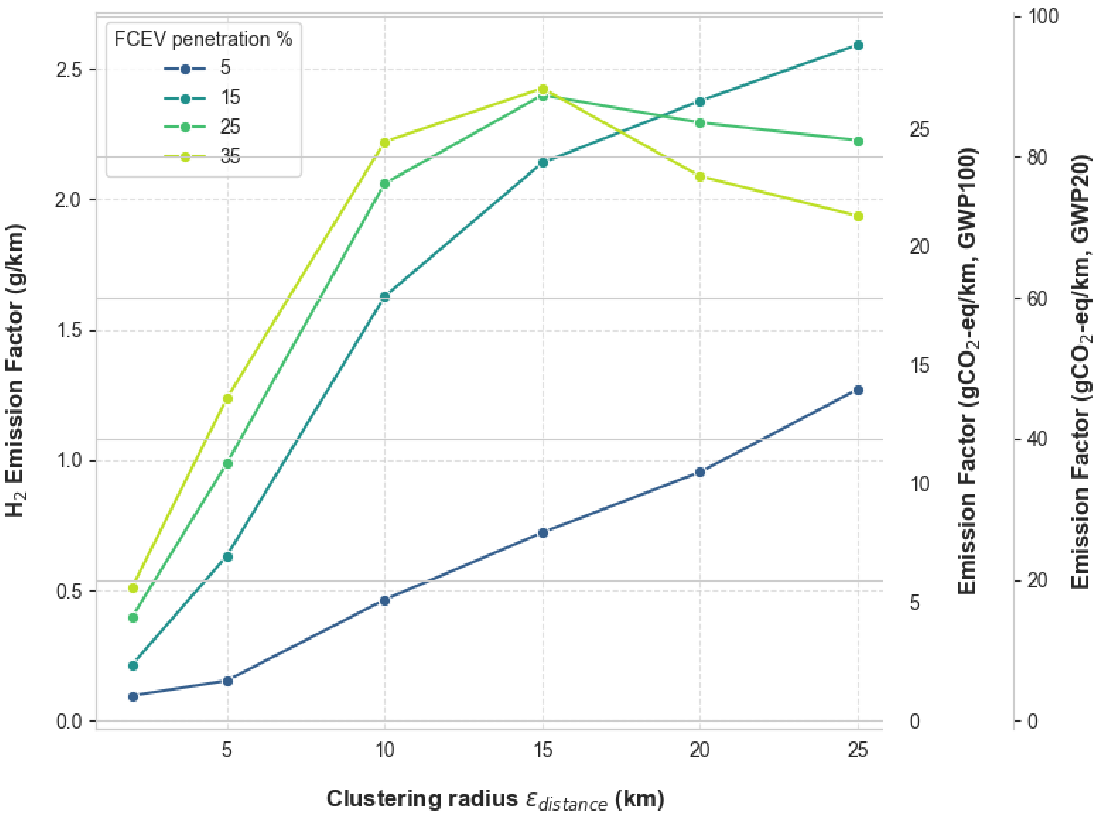
- Reduction of upto 25% costs by clustering HRSs

HRS Emission Factors 2050

By HRS Type



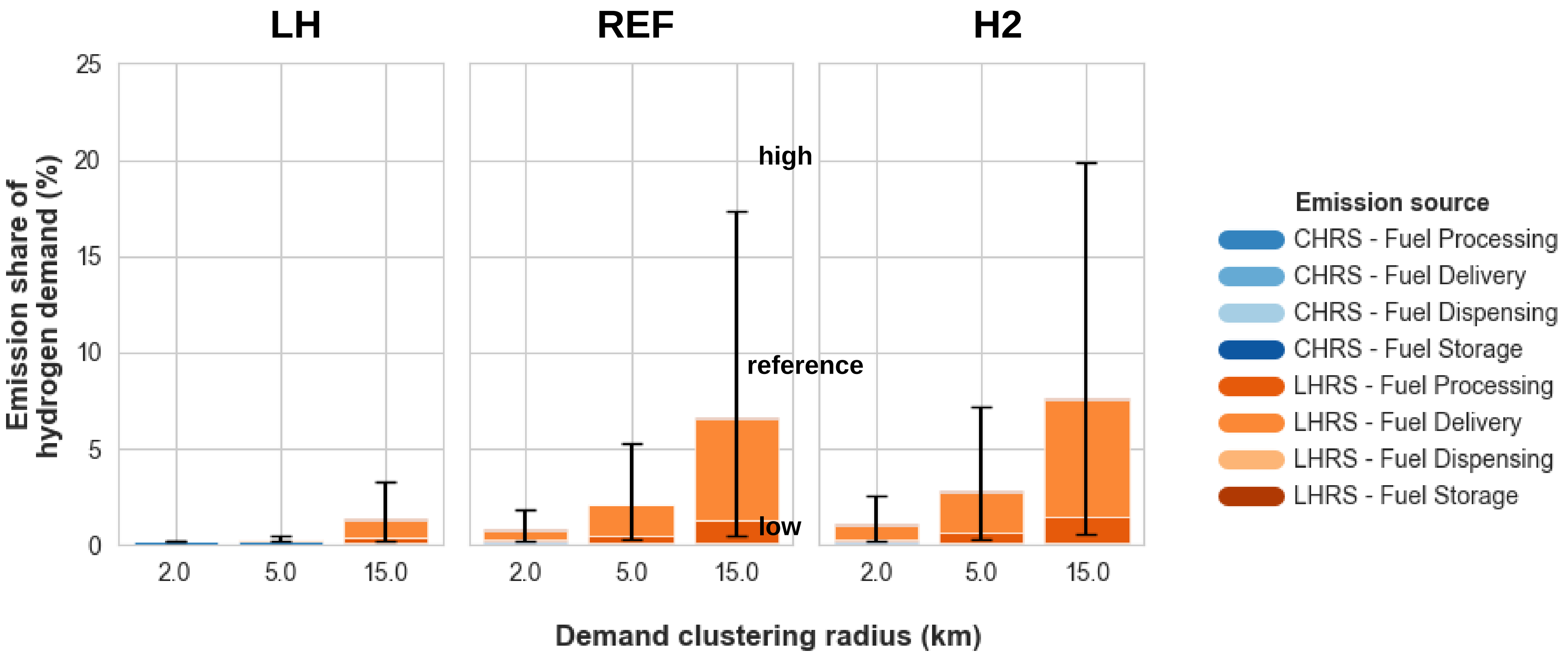
In Scenarios – 2050



- GWP100 CO_{2eq} emissions from HRS correspond to 1– 4% of projected tailpipe CO_2 emissions from HCVs in 2050.

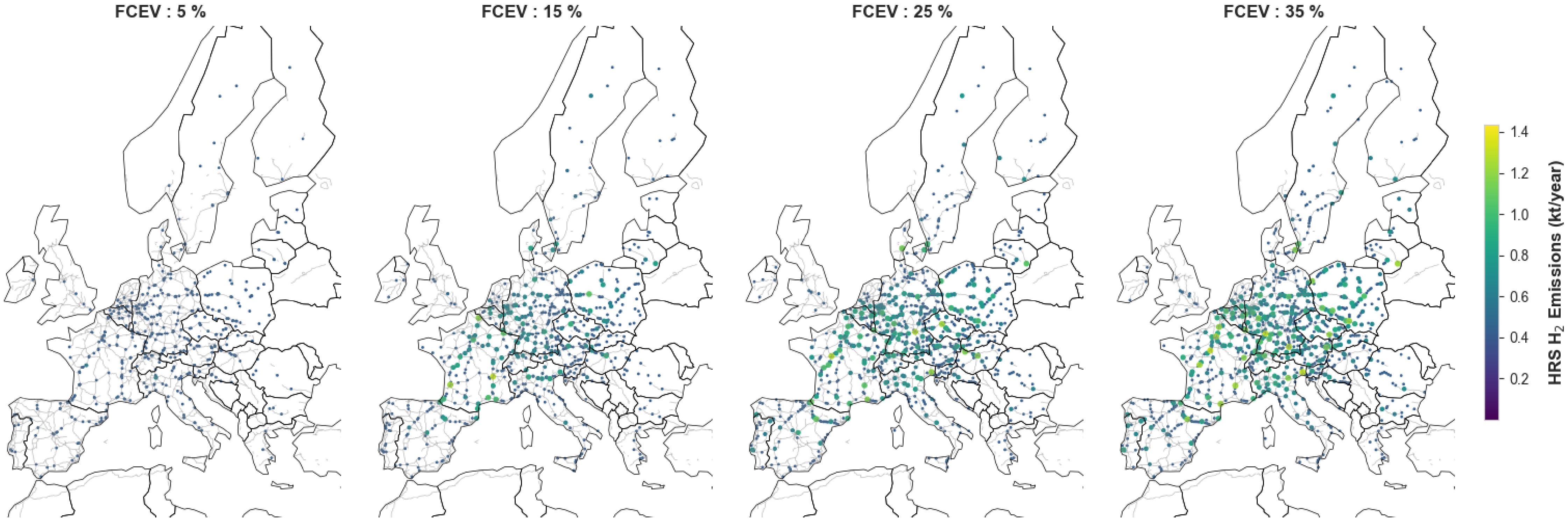
HRS Emission Factors 2050

Hydrogen refueling in the EU: emissions share and sensitivity for heavy-duty vehicles in 2050



- High variability in emission share depending on emission factor assumptions

HRS Emissions 2050 (in kilo-tonnes/year)



Total: 1.6 kt/year	Total: 66.3 kt/year	Total: 123.9 kt/year	Total: 175.4 kt/year
$\varepsilon_{distance}$: 5 km	$\varepsilon_{distance}$: 15 km	$\varepsilon_{distance}$: 15 km	$\varepsilon_{distance}$: 15 km

- For optimum selected clustering radius based number of LHRS and CHRS
- Use of hydrogen emission inventories to climate impact modelling in next project step to get GWP

Conclusions

- Focus on HRS emissions for hydrogen emission in transport scenarios for HCVs in EU till 2050
- Developed hydrogen emission inventory by **differentiating HRS type - LHRS and CHRS**
- **Use of optimization for meeting demand at low cost and distance** to HRS from trip refuelling edges
- Resultant emissions from HRS contribute **1- 4% of CO_{2eq}** tailpipe emissions from HCVs in 2050 based on **GWP100** and upto **15% based on GWP20**
- **High variability in emission shares** based on emission factor ranges by current literature and technology

Thank you!

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Project: CLEANLIEST

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9. *Speth, Daniel; Sauter, Verena; Plötz, Patrick (2022): Where to Charge Electric Trucks in Europe—Modelling a Charging Infrastructure Network. In World Electric Vehicle Journal 13 (9). DOI: 10.3390/wevj13090162.*

HRS Emission Factors

Emissions factor sensitivity

H_2- Source	Emission Scope	low	reference	high	Unit base
LHRS	LH2 Tanker Depressurisation and Purge Venting	**0.00**	**7.90**	**20.50**	% delivered fuel
LHRS	Station LH2 Storage Delivery Venting	**0.00**	**3.00**	**10.00**	% delivered fuel
LHRS	Station LH2 Storage Tank Boil-off Venting (4500 kg/day)	0.00	0.71	1.00	% capacity per day
LHRS	Station LH2 Storage Tank Boil-off Venting (18000 kg/day)	0.00	0.18	1.00	% capacity per day
LHRS	Station LH2 Storage Tank Boil-off Venting (30000 kg/day)	0.00	0.11	1.00	% capacity per day
LHRS	Station LH2 Cryopump Boil-off Venting	**0.00**	**1.60**	**3.00**	% delivered fuel
LHRS	Station Maintenance	0.85	0.85	0.85	% dispensed fuel
LHRS/CHRS	Station Dispenser Nozzle Disconnect	0.0002	0.0002	0.0002	kg/vehicle hose disconnect
LHRS/CHRS	Station Dispenser Nozzle Venting	0.0013	0.0013	0.0013	kg/vehicle hose disconnect
CHRS	CHRS Tube-Trailer Venting	0.00	0.00	0.00	%
CHRS	LP Storage Permeation	0.01	0.01	0.01	% stored fuel
CHRS	Compressor leakage	0.31	0.31	0.31	% dispensed fuel
LHRS/CHRS	HP Storage Permeation	0.01	0.01	0.01	% stored fuel

LHRS: H2 refueling station for liquefied H2; CHRS: H2 refueling stations for compressed H2; tank size based on HDSAM model

Optimisation Model

Not intended for final presentation

Variables

Variable $x[i,j] = Hydrogen\ demand\ of\ trucks\ of\ trip\ i\ fulfilled\ by\ HRS\ j\ (kg/day)$
Slack $ux[i] = Unfulfilled\ hydrogen\ demand\ of\ trucks\ of\ trip\ i\ fulfilled\ HRS\ j\ (kg/day)$

HRS Capacity $ca[j] = Capacity\ of\ HRS\ j$

Objective function

$$\min \sum_{(i,j)} x_{i,j}(c_j + \lambda_{dist}.\, dist_{i,j}/avg_{tank\ capacity}) + \sum_i penalty.\, ux_i$$

Constraints

$$\sum_i x_{i,j} < ca_j$$

Demand by all trips should be less than capacity of HRS

Parameters and Sensitivity

- $\varepsilon_{distance}$ Clustering radius
- $\boldsymbol{\lambda_{dist}}$ **:** Cost to extra travel to HRS per distance unit
- $\boldsymbol{penalty}$ **:** Cost to Unfulfilled demand of hydrogen

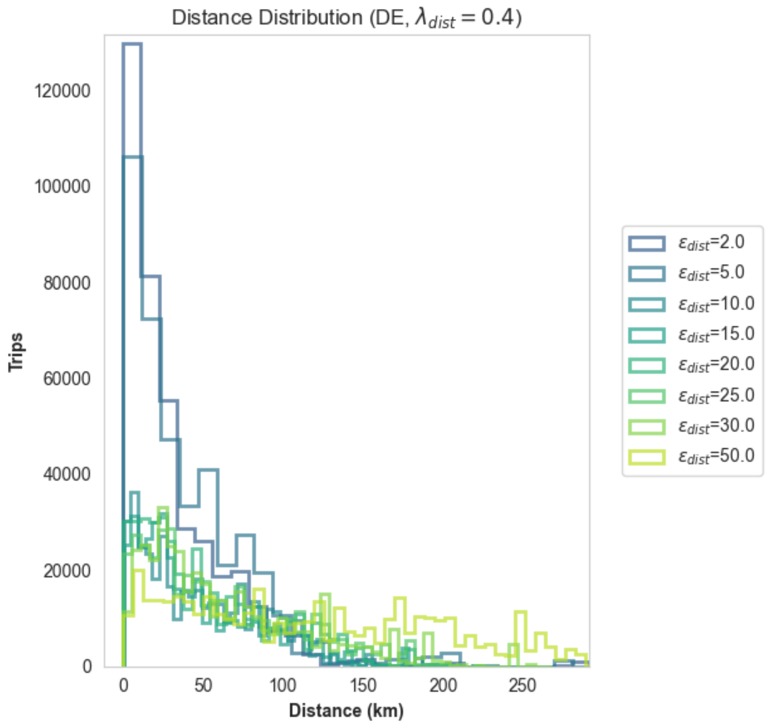
Model and model size

- **Optimizer** Pyomo + cbc runner

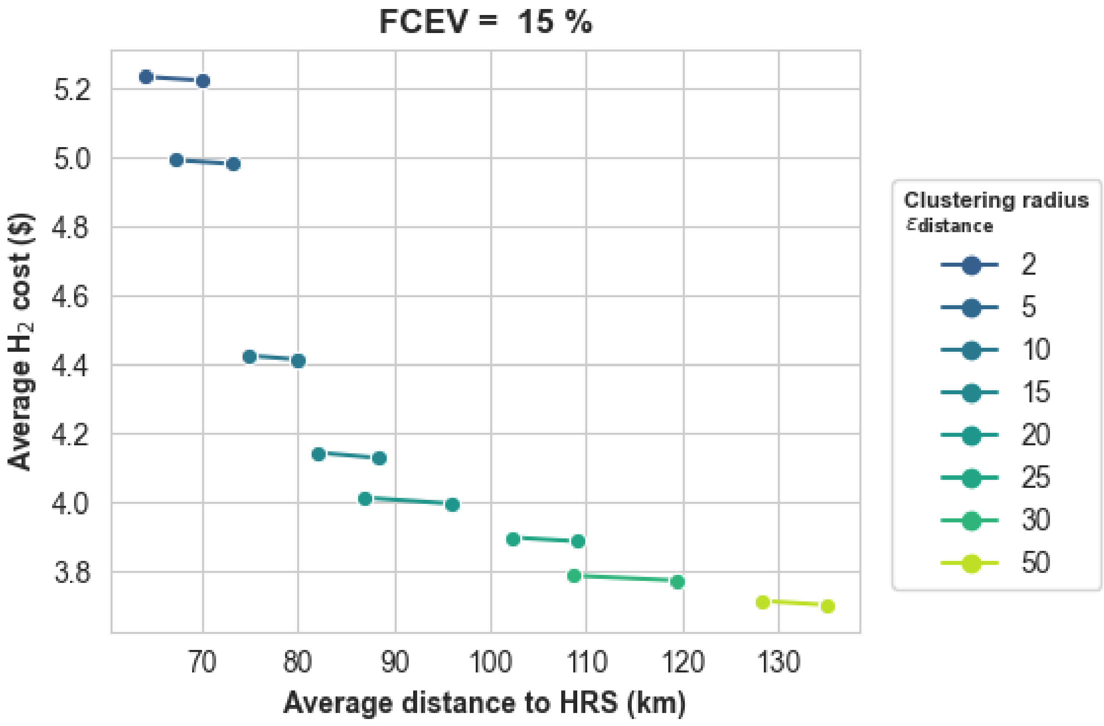
Problem has 8117 rows, 78909 columns (78909 with objective) and 149826 elements

HRS Optimization Model

Distance to HRS



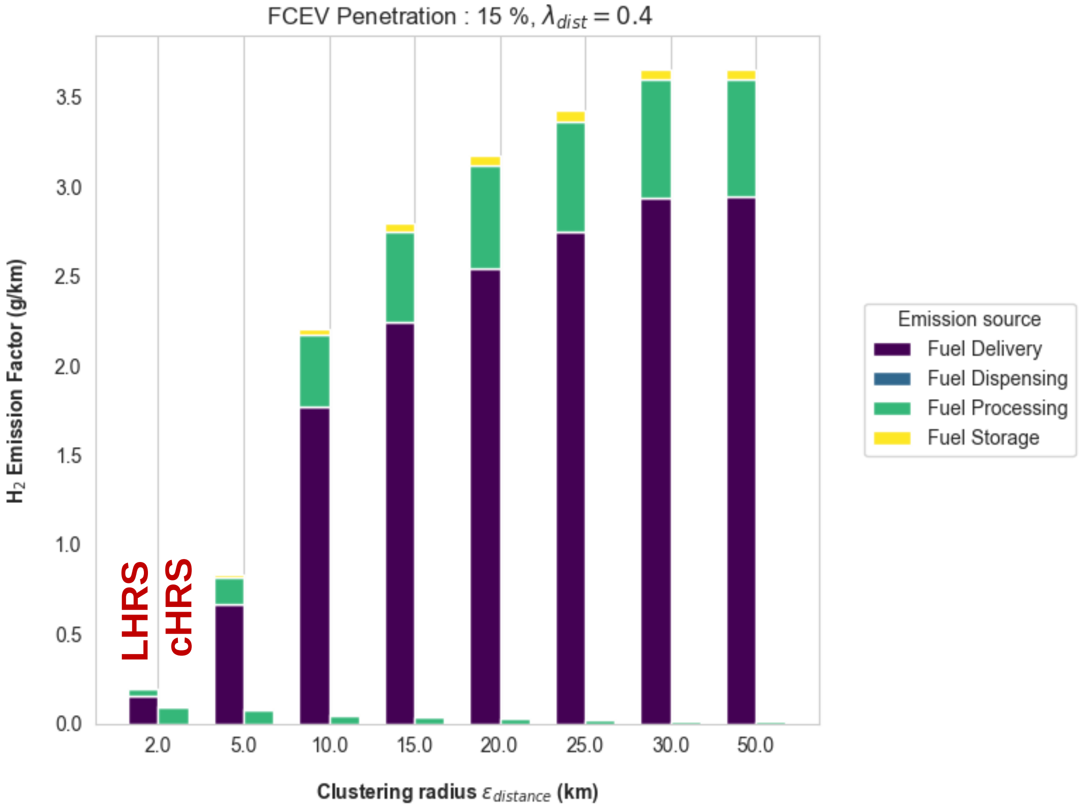
HRS Clustering



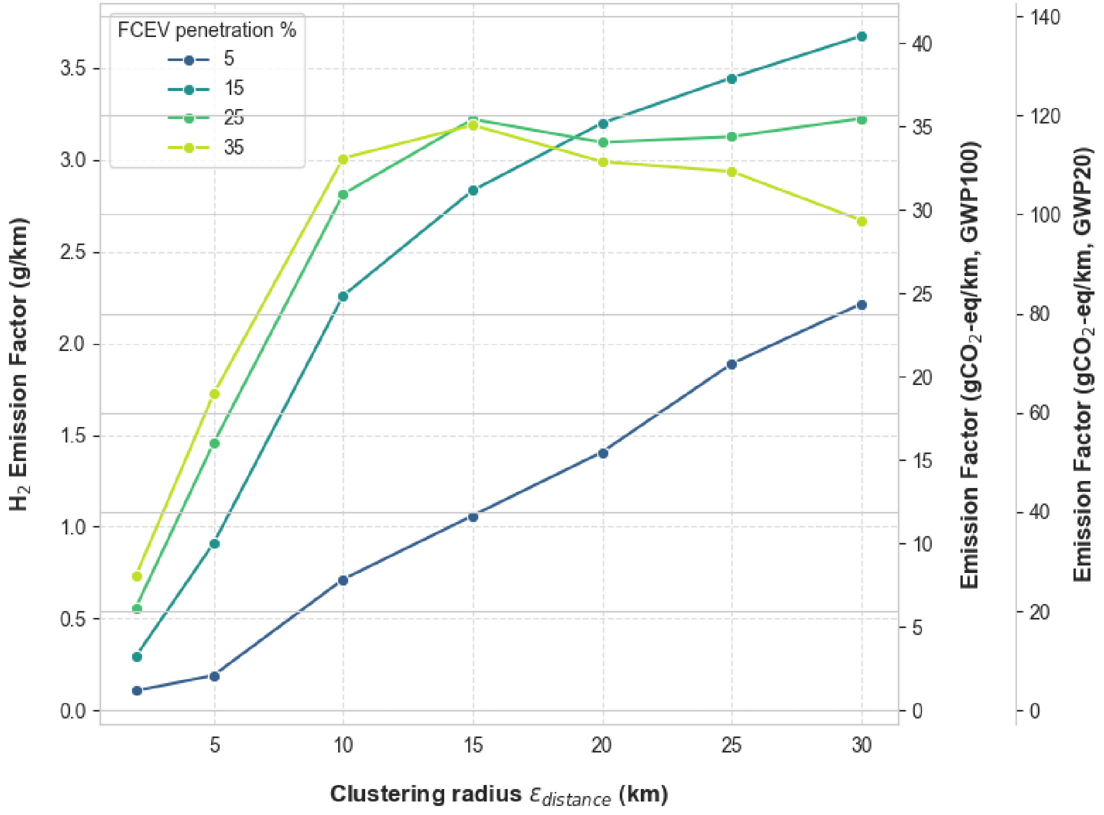
Not intended for final presentation

HRS Emission Factors 2030

HRS Type



Scenarios - 2030



- Higher emission factors in 2030 with same HRS installations due to higher LHRS use