A Real Options Analysis of the Siting and Cost-Efficient Layout of Charging Infrastructure for Fuel Cell and Battery Electric Vehicles

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FCN | Future Energy Consumer Needs and Behavior | E.ON Energy Research Center | RWTH AACHEN UNIVERSITY

Presentation outline

ILP: integer linear programming
ROA: real options analysis

1 INTRODUCTION

Introduction
- Motivation and research questions

2 LITERATURE REVIEW

Literature Review
- Identification of the state-of-the-art
- Fundamentals of e-mobility

3 FRAMEWORK DEFINITION

Framework Definition
- Definition of the framework conditions for model creation

4 MODEL DEFINITION

Model Definition
- ILP: Optimal spatial distribution
- ROA: Policy support switching

5 RESULT EVALUATION

Result Evaluation
- Analysis of model results

6 CONCLUSION AND OUTLOOK

Conclusion and Outlook
- Summary of key findings and outlook

Research questions

Two research questions were derived based on a literature review

Motivation

- **Greenhouse gas emissions:** Germany aims at reducing GHG emissions by min. 55%; mobility is responsible for around 20% of them (UBA 2021)
- **Political targets:** German government has set a target of 10 million e-vehicles and 1 million publicly accessible charging points by 2030 (EU 2021)
- **Charging infrastructure:** Massive investment in BEV and FCEV infrastructure is necessary for achieving the set targets

State-of-the-Art in Related Literature

- **Literature on spatial distribution:** A sharp increase in publications on BEVs can be observed in recent years (Pagani et al. 2019)
- **Comparative economic analysis literature:** Studies on competing charging infrastructure are still rare and hard to compare

Key question: In light of path dependencies and technological lock-ins, which alternative vehicle charging infrastructure/s should government support over time?

#1 Research Question #1

What is the optimal spatial distribution of the public charging infrastructure for BEVs or FCEVs in the ENSURE model region* for different e-mobility diffusion dynamics?

#2 Research Question #2

What economic costs and options for action result from the spatial distribution of charging infrastructure for BEVs and FCEVs from a policy maker's perspective (in light of the existing e-mobility policy goals)?

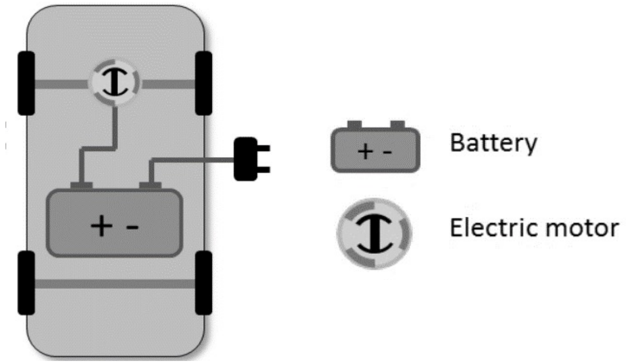
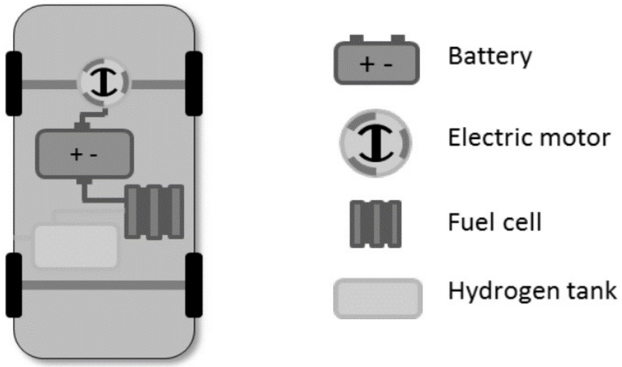
* District of Steinburg (Schleswig-Holstein); cf. www.ensure.de

Aim & Scope

- Considerable literature comparing the **economics of BEVs vs. FCEVs**
- Much less literature on **(competing) vehicle fueling/charging** infrastructure
- In our research we tackle the following **research gap**:
  1. Determination of the **optimal spatial distribution and density** of public BEV and FCEV charging stations (in different spatial settings, from rural to urban/cities)
  2. Simulation of **market diffusion scenarios** for the competing charging infrastructures
  3. Real options (binomial tree) **switching model** to determine the **optimal timing to switch policy support** for one or the other charging infrastructure (thus further fostering or breaking a technological lock-in situation)
  4. Application is to a **district in Schleswig-Holstein**, Northern Germany Steinfurt: 79,117 vehicles
  5. Derivation of **policy implications and recommendations**

Comparison BEV and FCEV

Refueling process and charging process are different between BEVs and FCEVs

	Battery Electric Vehicle (BEV)[4,5]	Fuel Cell Electric Vehicle (FCEV)
Energy source	Electricity	Hydrogen
Energy system	Battery ultracapacitor	Fuel cells
Charging modes	Public or private (home) charging	Public hydrogen filling station
Electric drive concept		
Charging duration	0.25 – 8 h	3 – 5 min
Range	Up to 600 km	Up to 756 km

Underlying framework data

Framework data for the creation of the models can be divided into four main categories

Framework Definition

Economic Costs
- Investment costs considering learning curves
- Costs electricity and hydrogen
- O&M costs and lifetime

Topology of Steinburg
- Area is divided into 30 squares with a size of 36 km² each
- 4 cluster categories are defined based on similarity coefficients

Demand and Accessibility
- Calculation of energy demand within maximum distance
- Maximum distance calculated based on accessibility of roadside fuel filling stations

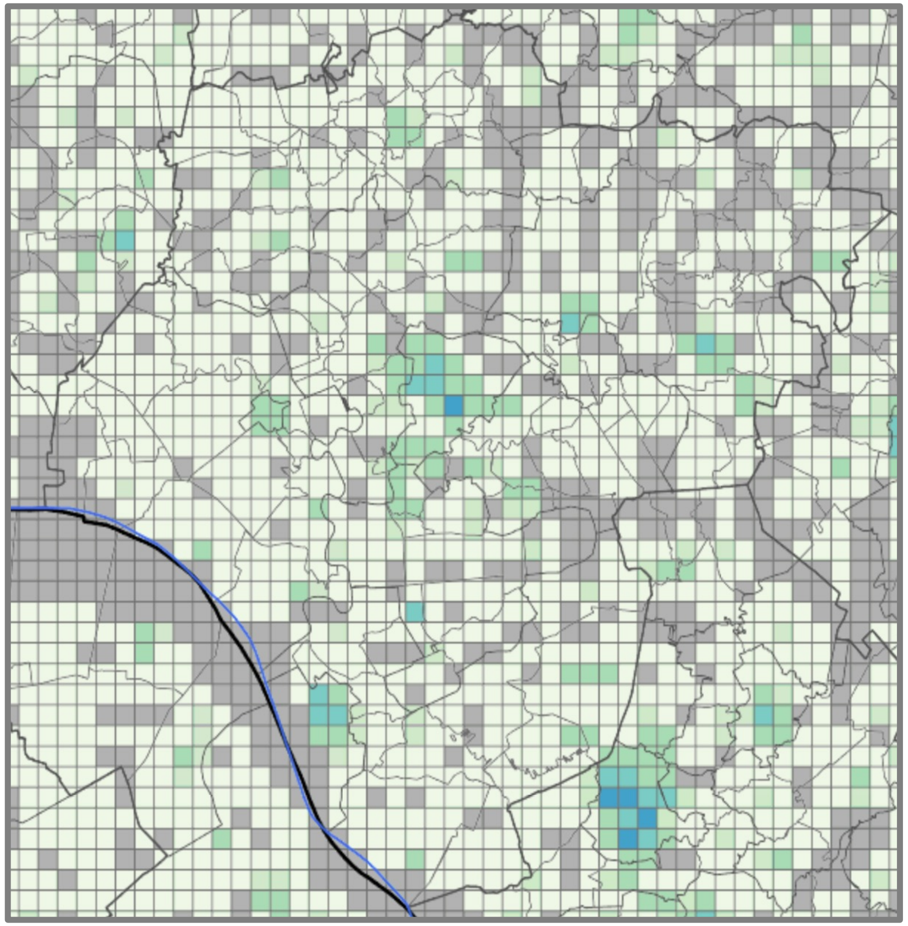
Diffusion Curves
- Sigmoid (S-shaped) diffusion curve is assumed for the calculations
- Three scenarios are defined based on the policy goal of 10 million electric vehicles 2030 in Germany

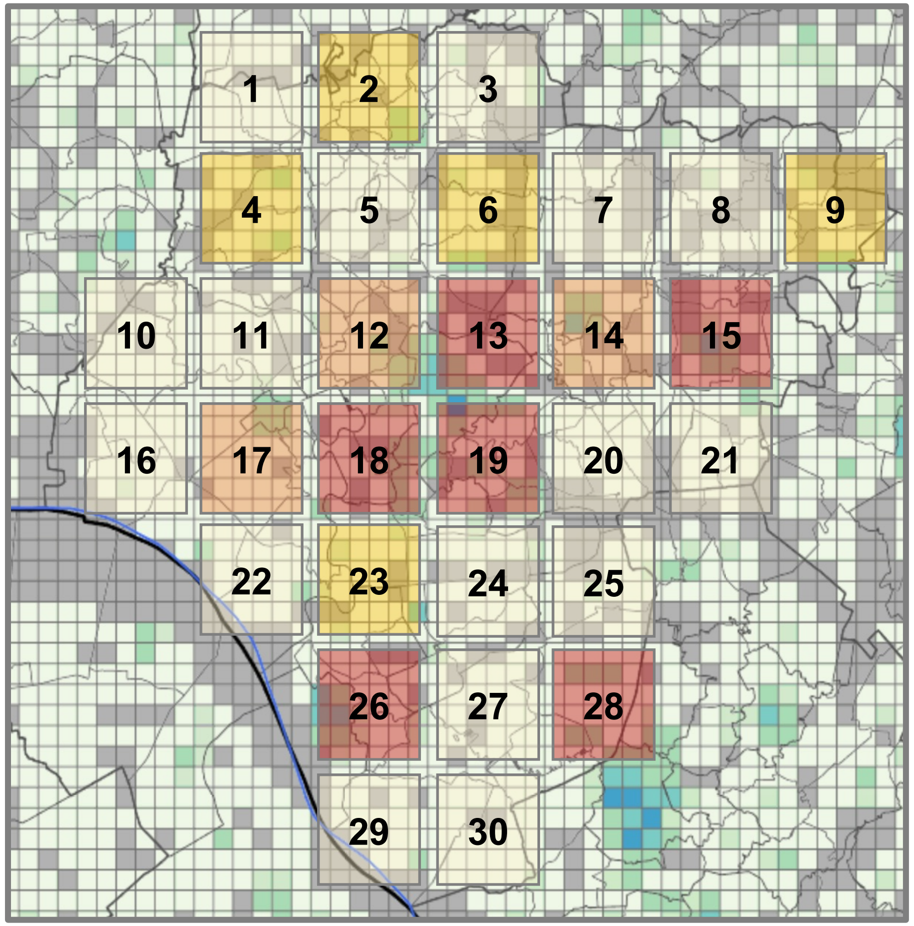
Cluster Analysis
- Single linkage method, a clustering algorithm based on similarity coefficient method (Anderberg 1973)

District clustering

Squares[6] were clustered and the location was recorded using Euclidean distances

Topology of Steinburg[6]





- Country
- Small municipality
- Large municipality
- City

Distance measure:
Euclidean distance

Methodical approach

A spatial distribution model and a real options model are used to tackle the two research questions

Spatial distribution model

- Investment costs
- Charging demand
- Topology of the district of Steinburg
- Accessibility of charging infrastructure

+

Real options model

- Learning curves through experience
- Market diffusion curves until 2050
- Economic framework data
- Beta-Pert cost distribution

Political decision-making aid

Spatial distribution model

The tradeoff of the model was defined considering the charge point utilization rates and the home charging share

Utilization Rates (FCEVs, BEVs) and Home Charging for BEVs

FCEVs
- Utilization rates for hydrogen stations used from an analysis of filling stations in the U.S.
- Value: 35% (van der Hoed 2013)

BEVs
- Values taken from a study in the Netherlands considering the difference between occupation and charging time (Kurz et al. 2019)
- Occupation: 32% Charging: 5%

Cluster	Pop. Share (%)	Home Charg. Share (%)
City	55	45
Large municipality	14	70
Small municipality	13	80
Country	18	90
Total / average	100	Ø 61[1)]

1) Transport & Environment (2020), Recharge: How many charge points will Europe and its Member States need in the 2020s.

Tradeoff Investigated

Minimum Investment Costs

vs.

Sufficient Accessibility

Spatial distribution model

The objective function minimizes the investment costs for a charging infrastructure operator

Exemplary Formulas for BEVs

(1)
$$min \sum_{i=0}^{n}(x_i \times stationcostBEV + y_i \times chargingpointcostBEV) + min \sum_{i=0}^{n}(a_i \times stationcostFCEV + b_i \times dispensercostFCEV)$$

(2)
$$shareBEV * needBEV_i \leq \sum_{\forall j \in (j | d_{ij} \leq maxdistancebev_i)} b_j \; \forall_{i \in I}$$

(3)
$$\sum_{i=0}^{n} b_i \geq minnumberchargingpointsBEV * shareBEV$$

(4)
$$b_i \leq maxchargingpointsperstationBEV * a_i$$

Explanation

Objective function
minimizes the costs for the construction of the charging infra-structure; a_i indicates the number of charging stations opened in node i and b_i the number of charging points

Constraint 1
ensures that the demand for charging points at node i is covered within the maximum distance

Constraint 2
ensures that the required total number of charging points is reached

Constraint 3
ensures that the number of charging points per charging station is met; also ensures that charging points can only be opened if a charging station is available

Real options analysis

Procedure for real options analysis requires a net present cost calculation and the selection of a distribution

Net Present Cost (NPC) Calculation

Calculation

- The calculated necessary charging infrastructure requirement from the spatial distribution model serves as the basis
- Three cost components are calculated
  - CAPEX: investment costs for charging infrastructure
  - OPEX: hydrogen / electricity prices
  - OPEX: O&M costs
- NPC results for the most probable scenario:

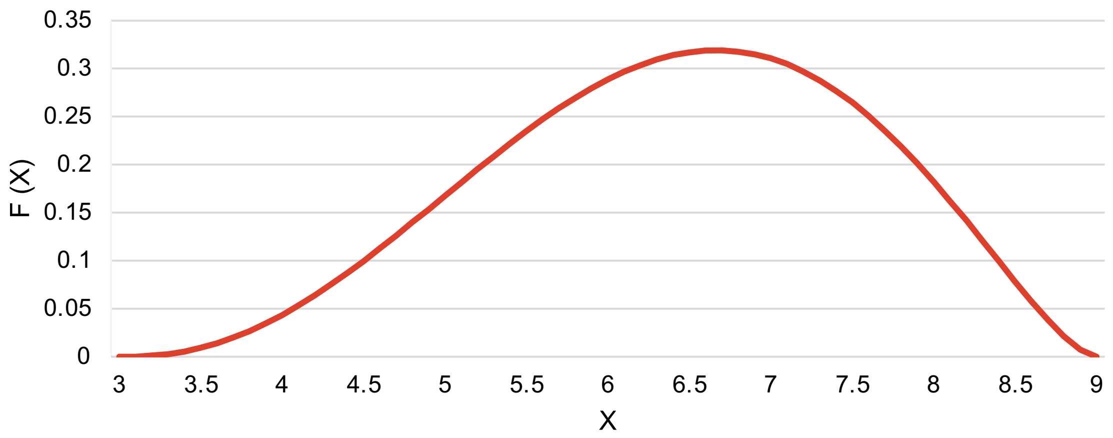
(million €)	BEV 2021-2050	FCEV 2021-2050
Infrastructure Cost	99	81
O&M Cost	66	40
Electricity Cost	405	706
Total	570	82

Beta-Pert Distribution for Up- and Down Factors

Distribution selection

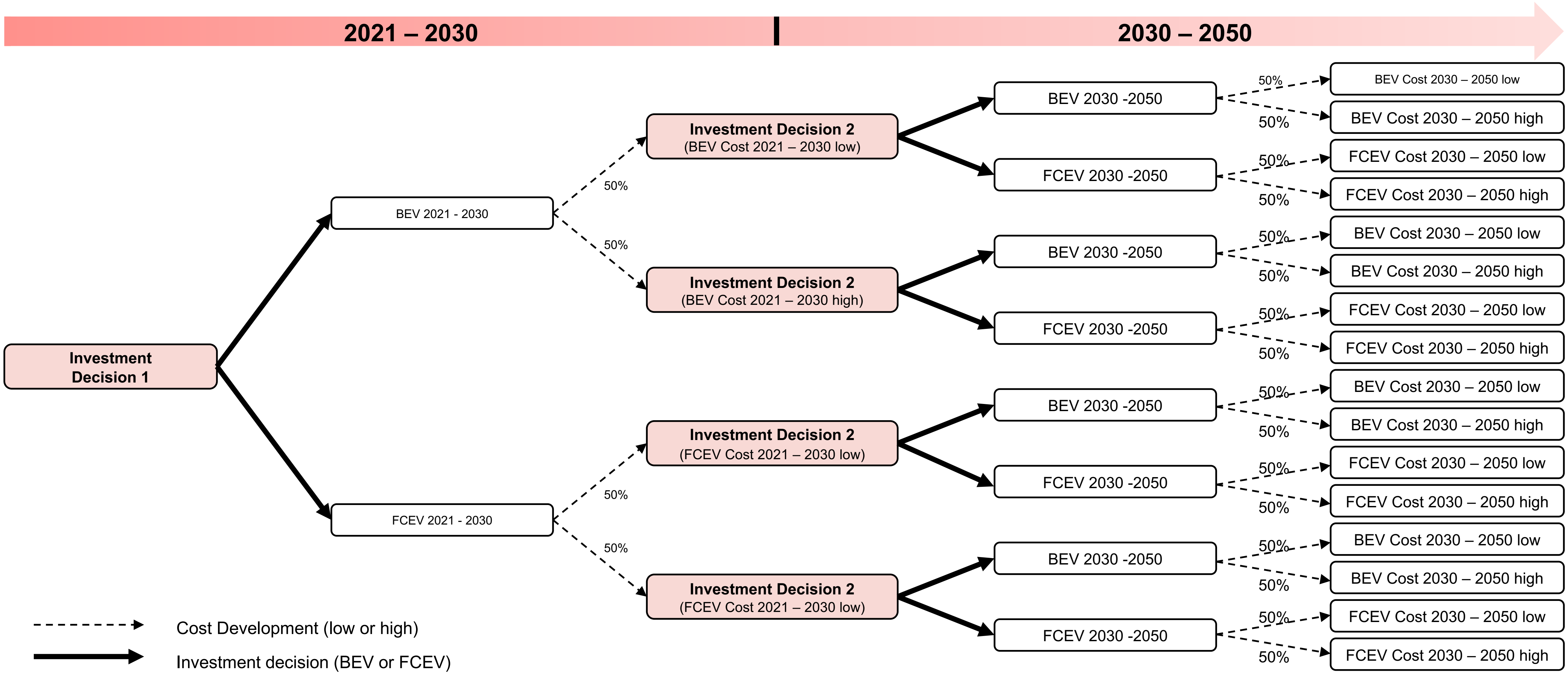
- Beta distribution was selected for the distribution of a cost function
- It considers, analogously to the triangular distribution, that cost distributions are usually asymmetrical
- Upper and lower quartiles are used as up- and down factors

Exemplary density curve of the PERT distribution



Real options analysis

The decision tree includes an option to switch for charging infrastructure expansion in 2030



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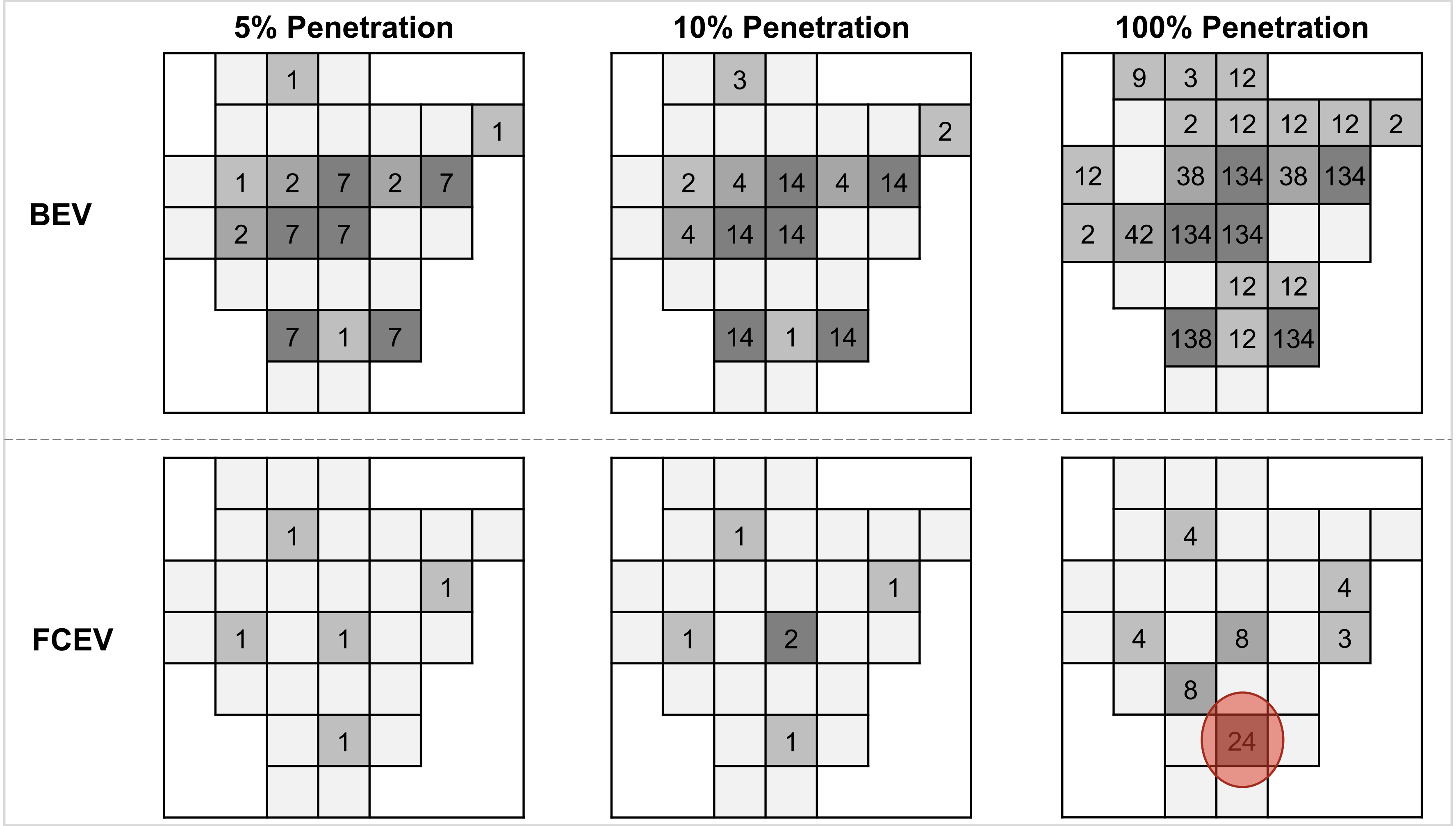
Spatial distribution model results

A significantly lower number of dispensers is required due to shorter charging time and higher utilization

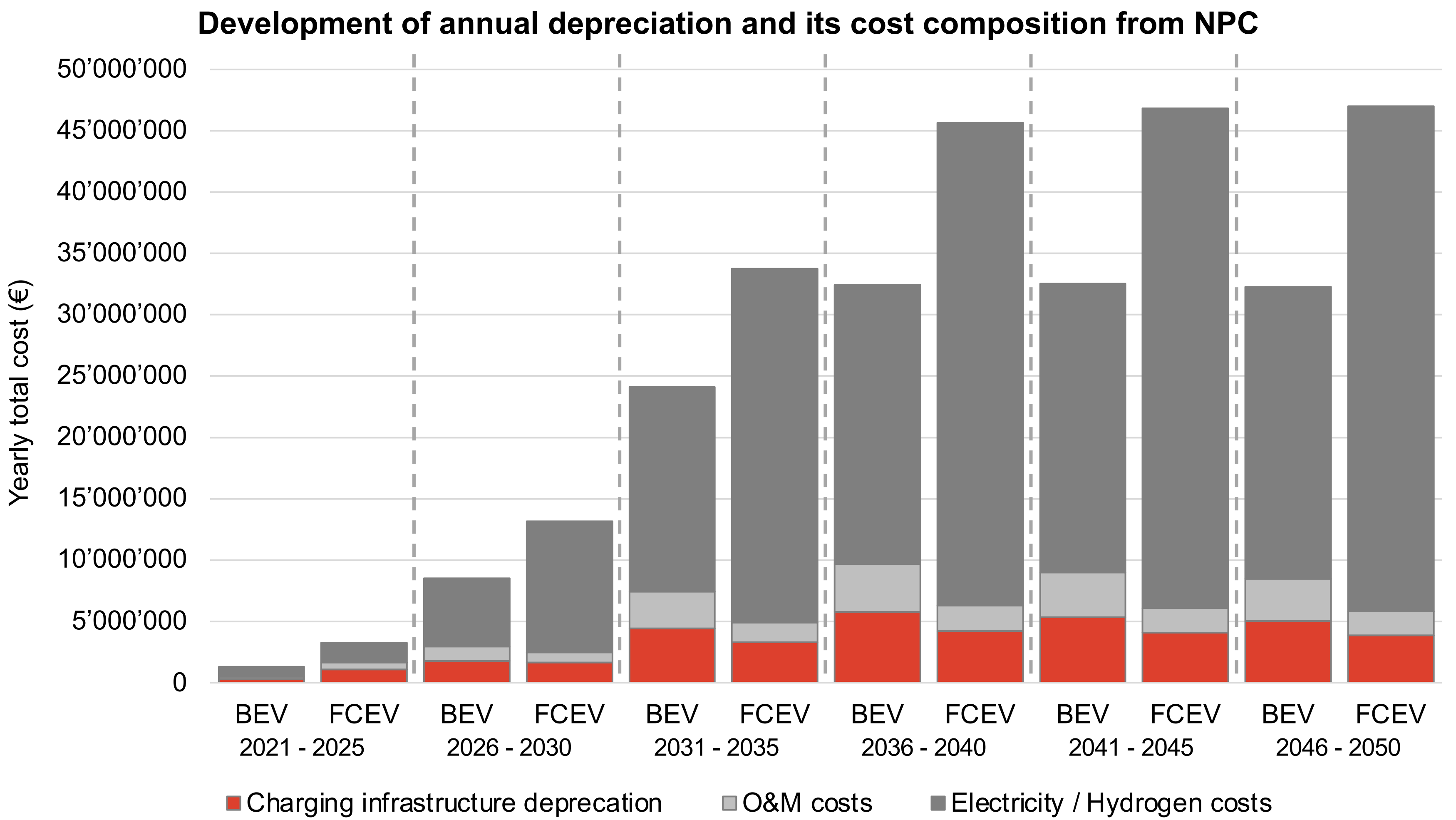


Insights

- Expansion for **BEVs is linear:** doubling the penetration rate is accompanied by a doubling of charging stations
- Expansion for **FCEVs not linear:** high initial investments
- **Highest BEV charging** infrastructure demand in the squares of the "city" category
- **FCEV charging locations** are found in the vicinity of the city squares and not inside the city

Net present cost calculation results

The pure charging infrastructure costs for FCEVs are lower whereas the total charging costs are higher



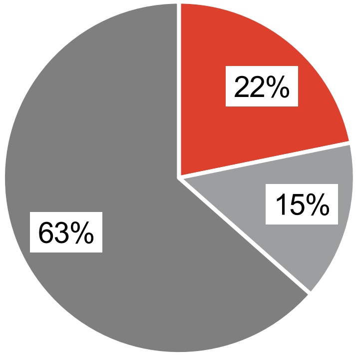
Insights

- Cost of charging for **FCEVs is 149% higher** from 2021 to 2025, it is only **46%** higher from 2046 to 2050
- Costs of FCEV charging infrastructure are lower than the costs for BEV charging infrastructure (ignoring the costs for hydrogen or electricity)
- **Home charging is included** in the NPC calculation (61% of charging occurs at home)

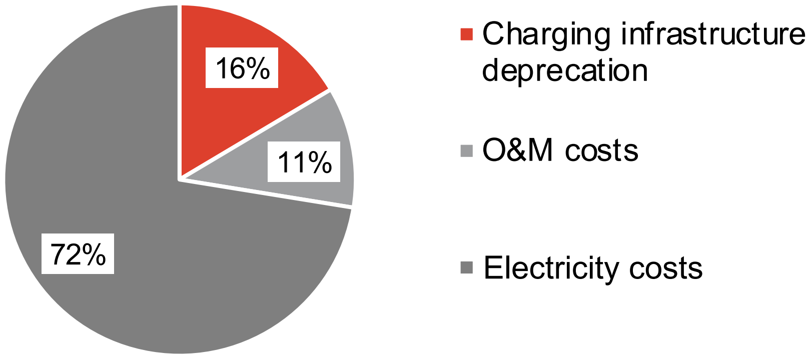
Net present cost calculation results

→ Cost composition is dominated by electricity and hydrogen prices and the share increases in the long term

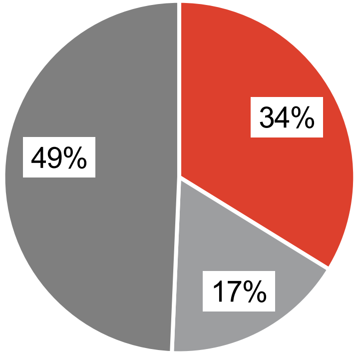
BEV cost composition 2021–2025



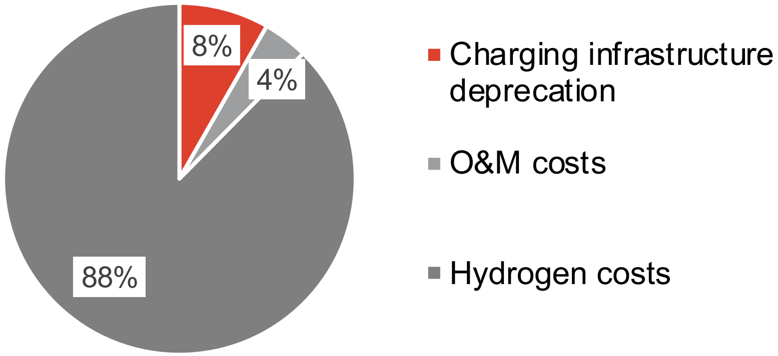
BEV cost composition 2046–2050



FCEV cost composition 2021–2025



FCEV cost composition 2046–2050



Insights

- Cost share of electricity and water **increases strongly between the** observation periods 2021 to 2025 and 2045 to 2050
- **Main reason:** the investment costs for charging infrastructure decrease due to the **learning cost curve**
- For FCEVs, the increase in the share of hydrogen costs from 49% to 88% can also explained high infra-structure **investments at the beginning**

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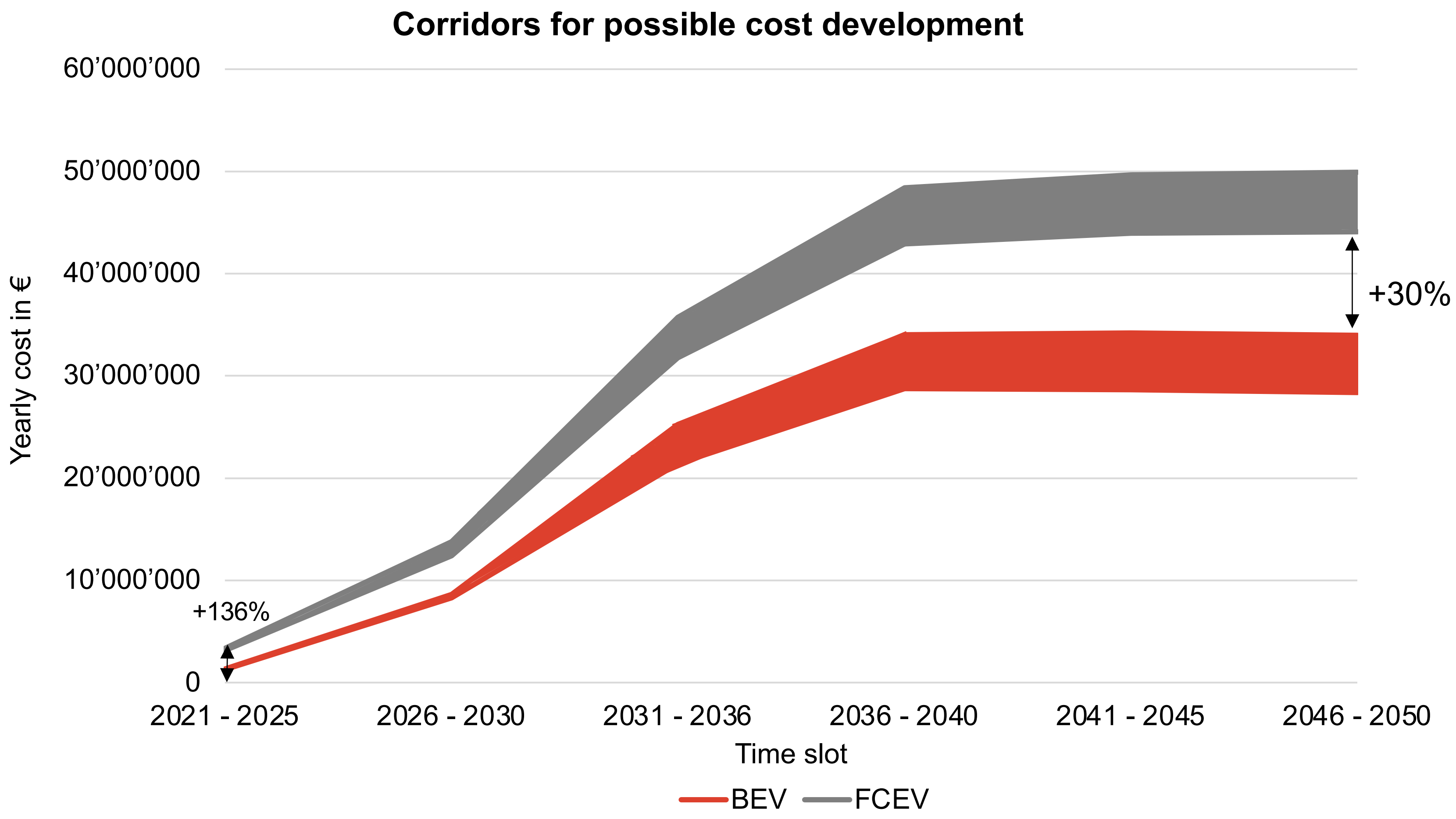
Real options analysis results

Due to strict cost dominance a use of the option to switch is not a real / viable decision option



Insights

- Favorable cost de-velopment for FCEVs is **always higher** than the unfavorable cost for BEVs
- **Total cost BEVs** between €508–598 mill. (2021–2050)
- **Total cost FCEVs** between €777–874 mill.
- Due to the **strict cost dominance**, the use of the option to switch in 2030 is not a real / viable decision option

Additional scenario results

Under certain conditions the use of the option to switch can make sense

Adjustments to the Framework Data

Adjustment electricity price

- A study commissioned by E.ON calculated an investment need of between **€1.1–5.0 bn** for integrating e-mobility (T&E 2020)
- **Investment level** depends on charging management: uncontrolled charging (€400 per vehicle); grid-friendly controlled charging (€180 per vehicle); market-based charging behavior (€800 per vehicle)

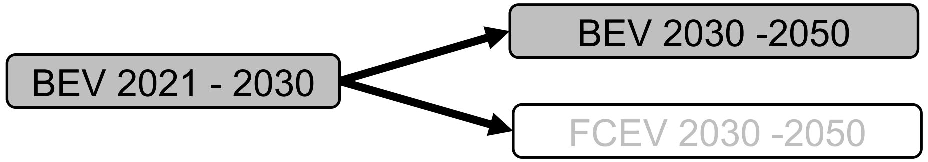
Adjustment hydrogen price: -60% production costs after 2030

	Hydrogen [€ / kg] Framework data[a,b]	Hydrogen [€ / kg] Additional scenario[c]
2021–2030 low	5.2	5.2
2021–2030 prob.	5.5	5.5
2021–2030 high	5.7	5.7
2031–2050 low	4.5	3.0
2031–2050 prob.	4.7	3.2
2031–2050 high	4.9	3.4

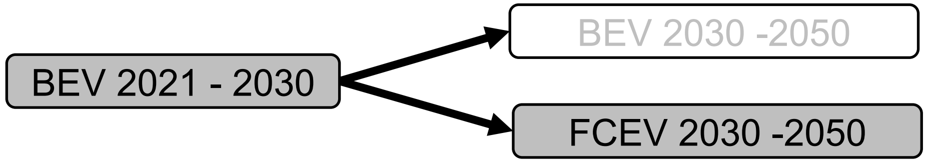
a IRENA (2020); b Reuß et al. (2019); c Hydrogen Council (2021)

Results of the Additional ("Extreme") Scenario

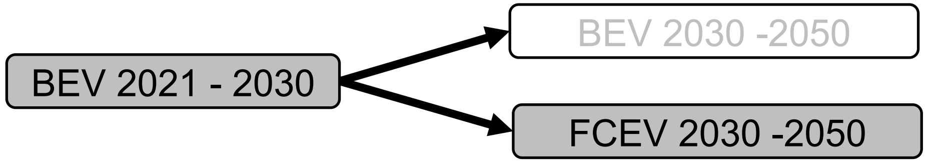
Grid-serving charging control (€180 per vehicle)



Uncontrolled charging behavior (€400 per vehicle)

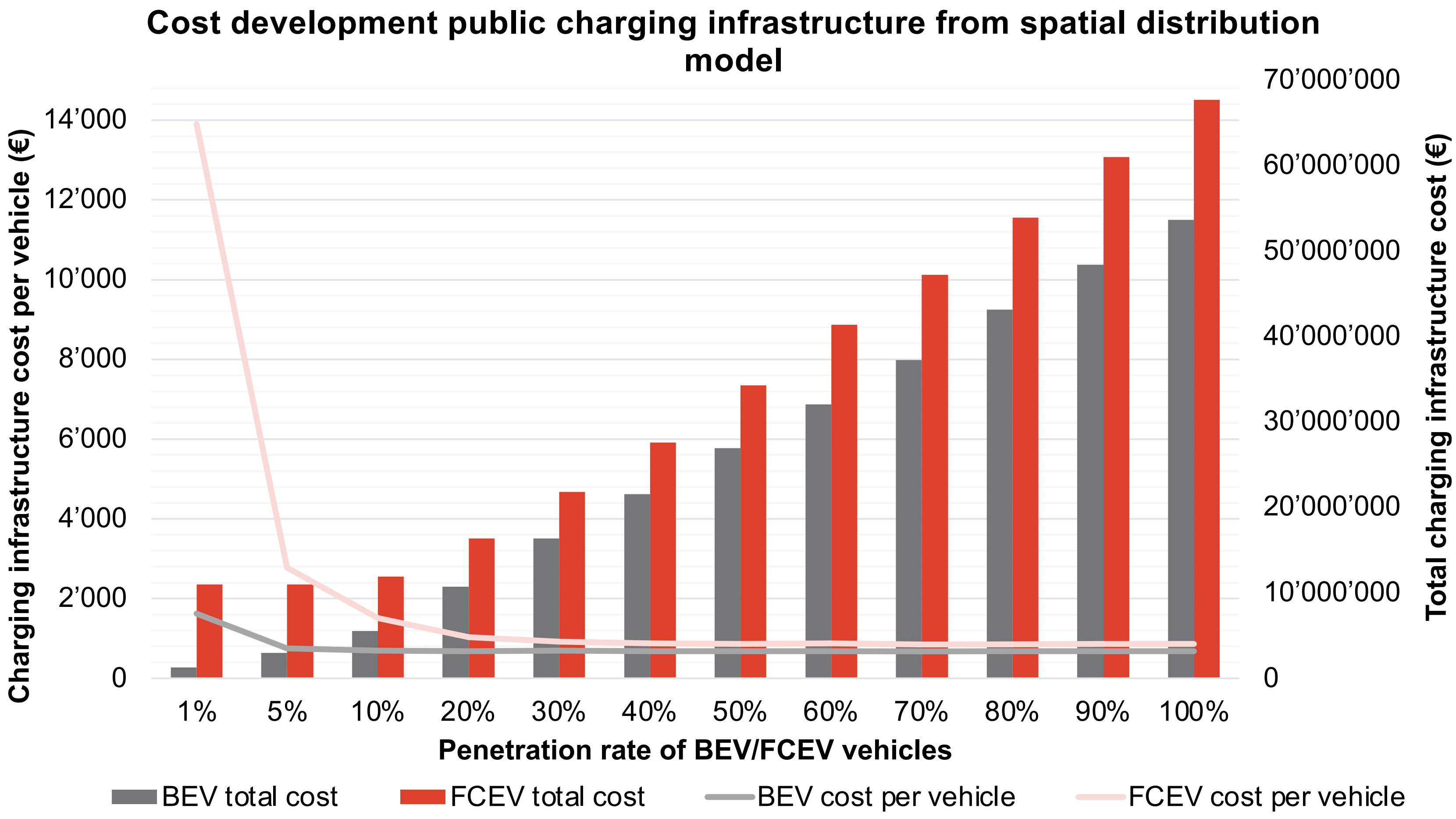


Market-based charging behavior (€800 per vehicle)



Backup slide: Spatial distribution model results

Public charging infrastructure for FCEVs is characterized by very high costs at low penetration rates



Insights

- Initial overview of the cost development of **public charging** infrastructure
- At 1% penetration rate for public charging infrastructure, costs are **750% higher** for FCEVs than for BEVs
- At **higher diffusion dynamics**, values do converge
- At a penetration rate of 100%, public charging infrastructure for FCEVs is only **26% more costly** than for BEVs

Summary and outlook

The key results provide a good basis for the further analysis and detailing of the spatial distribution

Key Results

Influence of penetration rates

- High investments in FCEV charging infrastructure are necessary to sufficiently cover user needs even at low FCEV penetration rates
- Pure infrastructure costs for FCEVs are lower at high penetration rates

Electricity and hydrogen as cost drivers

- Electricity and hydrogen costs dominate the total costs for the charging infrastructure

Necessary cost development hydrogen

- Average production costs for hydrogen must fall into the range €1.2 to €1.7 per kg in the period 2031 to 2050

Next Steps

1. **Detail increase:** increase the level of detail of the spatial distribution model and include possible revenues for operators in real options analysis
2. **Cost development:** regularly analyze the development of electricity and hydrogen prices as main cost drivers
3. **Technology:** beside economic calculations latest technological developments and their potential should be analyzed

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