MODELING MARKET DIFFUSION OF PLUG-IN ELECTRIC VEHICLES WITH REAL WORLD DRIVING DATA – DATA, METHODS AND RESULTS

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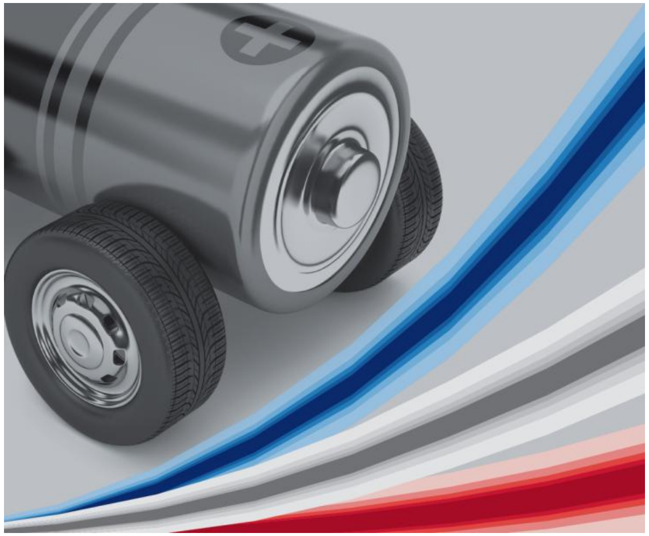
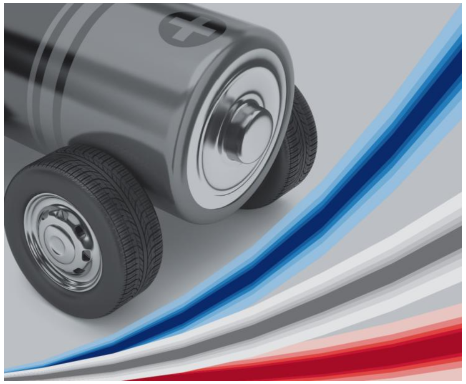
Fraunhofer Institute for Systems and Innovation Research ISI



Presentation at Argonne National Lab, October, 26th 2016

Agenda



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2 Motivation

3 Data, Methods and Parameters

- Driving data
- Market diffusion model ALADIN

4 Central results

- Total cost of ownership (TCO) of electric vehicles and TCO gaps
- Market diffusion scenarios for Germany

5 Conclusions and discussion

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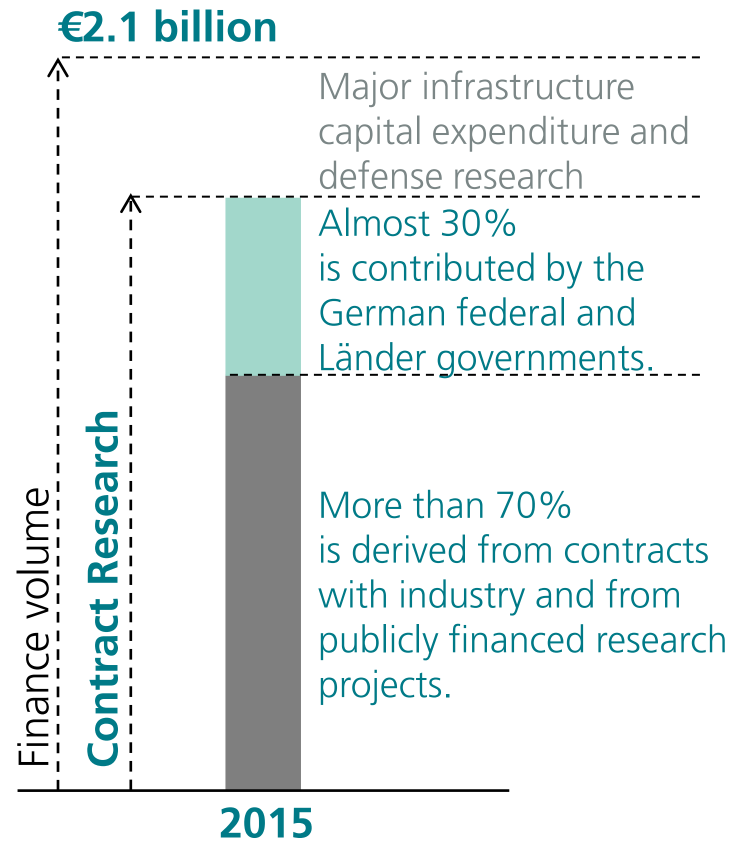
The Fraunhofer-Gesellschaft at a glance

The Fraunhofer-Gesellschaft undertakes applied research of direct utility to private and public enterprise and of wide benefit to society.

24,000 staff

67 institutes and research units



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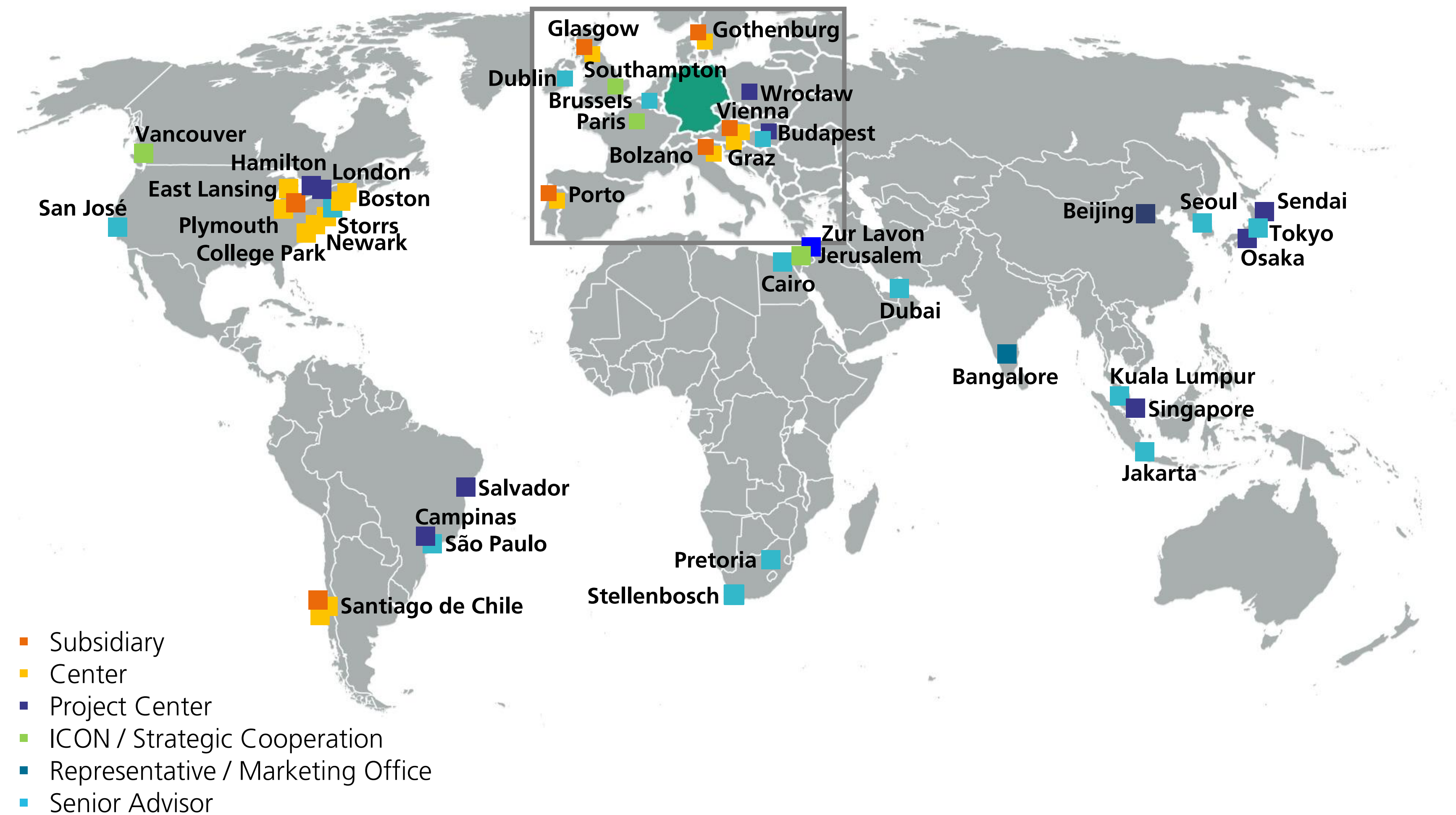
Fraunhofer worldwide



US headquarters in Plymouth, Michigan
220 employees in the US
http://www.fraunhofer.org/

Fraunhofer ISI - Facts and Figures

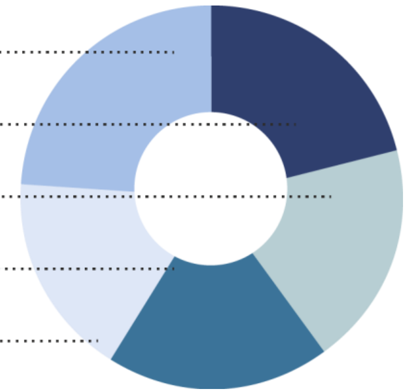
Broadly based know-how

Total number of staff
31 Dec 2015: **233**

About 60 work on energy systems and energy policy

About 10-15 work on transportation and new vehicle technologies

24% Social scientists
21% Economists
19% Natural / life scientists
19% Engineers
17% Industrial engineers

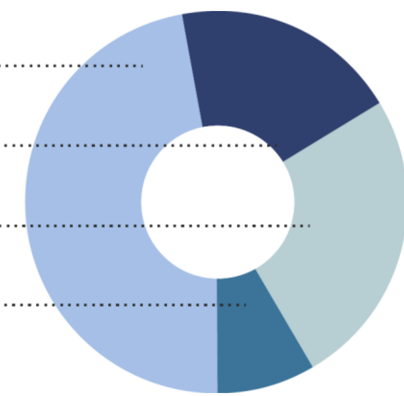


Clients*

Budget 2015:
approx. € 21 million

400 research and consultancy projects per year

47% Public sector national
19% EU
25% Industry
9% Other R&D and Research promotion



* percentage of total

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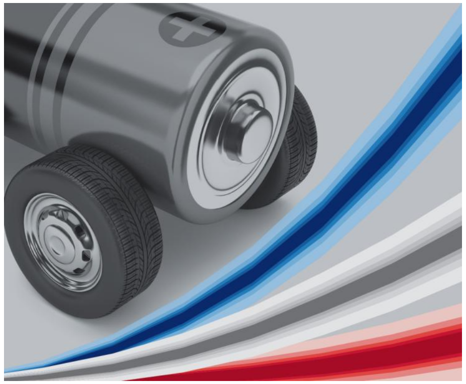

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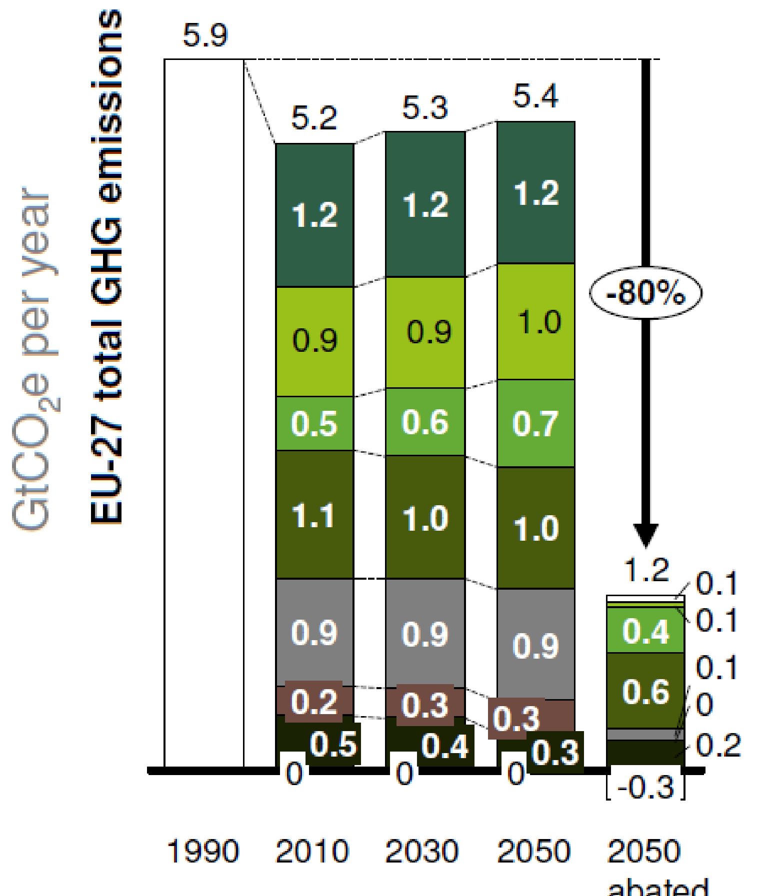
A drastic reduction of CO_2 emissions is required to reach Europe's climate targets.



Source: www.roadmap2050.eu

- EU target: reduction of GHG emissions by 80% compared to 1990
- Transport sector has to contribute, but goals not achievable with combustion engines vehicles
- Electric vehicles with renewable electricity offer large potentials
- Large number of electric vehicles can have significant impact on grid and electricity consumption
- **Policy makers and industry need reliable market diffusion models**

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Different propulsion technologies are available as electric vehicles.

There are different electric vehicle and hybrid vehicle concepts

- Only electric propulsion: BEV – *Battery electric vehicle*
- Hybrids: *plug-in-hybrid electric vehicle* and *range extended electric vehicle*

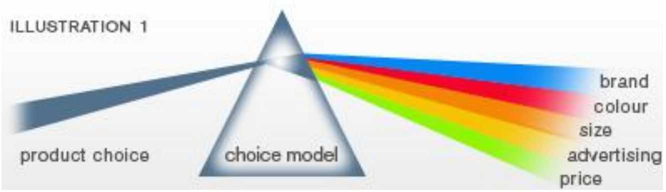
Key parameters		Electric vehicles		
Property	**Combustion engine vehicle**	**Plug-in hybrid vehicle (PHEV)**	**Range extender vehicle (REEV)**	**Battery electric vehicle (BEV)**
Range	> 700 km	30 + 600 km	80 + 600 km	< 150 km
Refuelling frequency	Every 2 weeks	Every day+ When needed	Every day + When needed	Every third day or 30% every day
Refuelling duration	3 minutes	3 minutes + 2 hours	3 minutes + 4 hours	1/2 - 8 hours
Electrification	Combustion engine			Electric motor

Different methods & diffusion models are available to estimate market evolution.

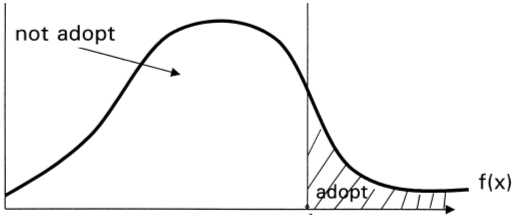
1. **Aggregated models (~top-down)**
   - Diffusion of technology highly aggregated
   - *Examples*: logistic, Bass, and Gompertz diffusion (cp. Geroski (2009): Models of technology diffusion)
   - Highly sensitive in early market phase

$$\frac{d}{dt}N(t) = rN\left(1 - \frac{N}{N_{\max}}\right)$$

2. **Discrete choice models**
   - Very common in transport demand models
   - Utility maximisation interpretation established (cp. Train (2009): Discrete choice methods and simulation)
   - Difficult to apply to completely new products or technologies (participants never actually drove an EV)



3. **Agent-based models (~bottom-up)**
   - Acknowledge variety of users & properties change in time
   - Product characteristics distribution is required
   - Our model ALADIN is an agent-based model



For a slightly similar yet independent classification see B.M. Al-Alawi & T.H. Bradley (2013): Review of hybrid, plug- in hybrid, and electric vehicle market modeling Studies. Renewable and Sustainable Energy Reviews 21, pp. 190–203. Distinction there: Diffusion rate, consumer choice, and agent based.

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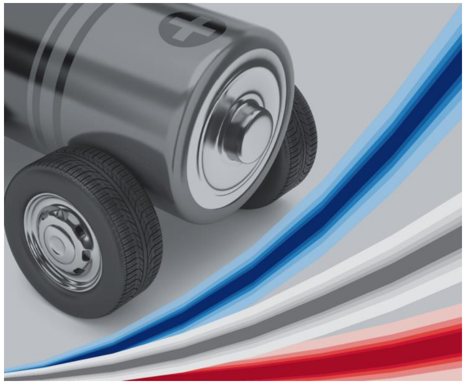

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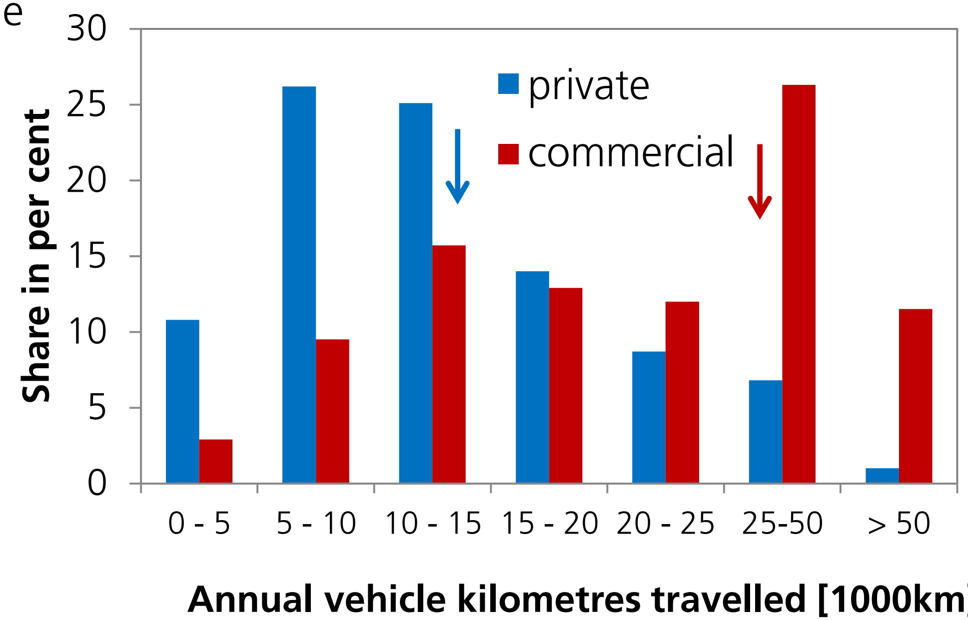
Driving differs significantly between different individuals and user groups.

- **Annual vehicle kilometres travelled vary strongly between vehicle sizes and users**
- Variety of usage not reducible to simple influence factors (e.g. vehicle size, city size or industrial branches)
- Average values (↓) cannot reproduce this heterogeneity
- **Limited electrical range** of BEVs important in buying decision
- **Electric driving shares** of PHEVs and REEVs important for realistic TCOs



➢ Real-world **driving profiles** allow a **more realistic TCO-calculation** and explicit inclusion of the diversity in car usage.

➢ In ALADIN ~7,000 driving profiles with ~250,000 single trips are analysed.

Source: Own analysis based on MiD (2002).

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We use driving profiles of private and commercial users.

- **Long observation periods** are crucial for EV characteristics
  - Limited range of BEVs, electric driving share of PHEVs/REEVs
  - Usage varies largely between users and days (esp. weekday vs. weekend)

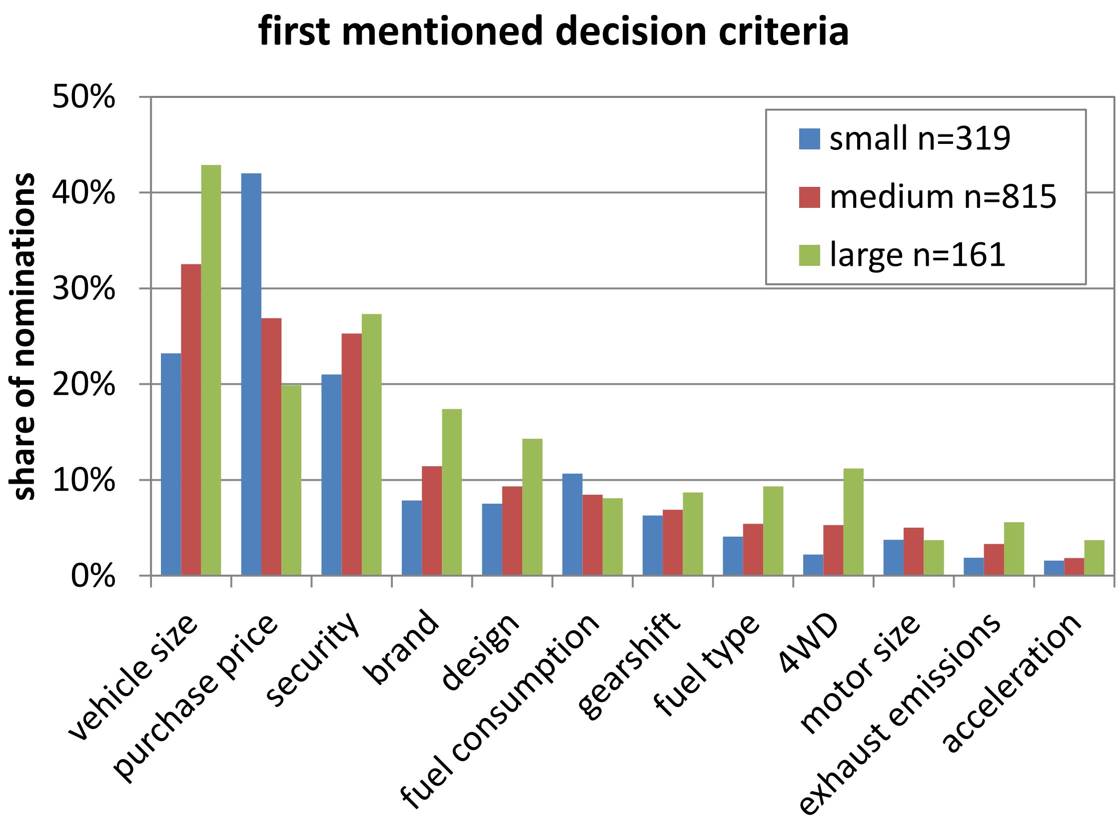
attribute	Private and company cars **German Mobility Panel (MOP)* 1994 – 2011**	Fleet vehicles **Fraunhofer ISI REM 2030-Data**
Data collection design	Questionnaire	GPS-tracking
Observation period	**7 days**	**average 18.7 days**
Data set size	6,339 vehicles ~190,000 single trips Socio-demographic data	604 vehicles 80,899 trips company information

- Other sources (MiD or KiD 2002/2008) have larger samples but only one day observation
- Similar data is available for other countries

* MOP considers people and their movements, a mapping to vehicles can only be done in unambiguous cases, see Kley (2011).

Motivation: Important factors in vehicle purchase decisions and how to model them

Important factors in private vehicle purchase decision:



Considered in ALADIN:

- ✓ Vehicle size
- ✓ Purchase price
- ✓ Brand
- ✓ Fuel consumption
- ✓ Fuel type (partly)
- ✓ Emissions (partly)

Assumed to be **equal**:

- ○ Security
- ○ Design
- ○ Acceleration

Not included:

- – Gearshift
- – Motor size
- – 4WD

Source: Own illustration after Peters, A. and P. d. Haan (2006)

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ALADIN – **Al**ternative **A**utomobiles **D**iffusion and **In**frastructure – model overview

User-specific analysis

User behaviour

Driving profiles

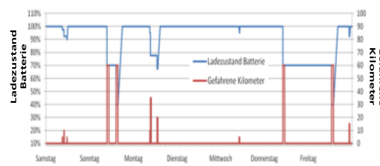
- All trips over at least one week: distance, duration, purpose, dep. & arrival time
- Owner information: gender, age, income, garage, city size
- Vehicle size, brand, age

EV user acceptance

- Willingness-to-pay-more by adopter status (innov., early adopter, majority, laggards)
- Limited charging infrastruc.
- Limited vehicle choice EVs

Model steps

Individual EV simulation



For each user i:

- Feasibility BEV
- Electric driving share PHEV / REEV

Individual utility maximisation

For each user i and propulsion technology p:

$$\max_{p}\left(-\mathrm{TCO}_{ip}+\text{willingness-to-pay-more}_{ip}+\right.\\ \left.-\text{limited choice}_{ip}-\text{home charging cost}_{ip}\right)$$

- Optimal vehicle choice for each user

Parameters

Vehicle dependent

- *Technical*: battery sizes, DoD, el./conv. consumption
- *Economical*: car prices, taxes, O&M costs, resale values
- *Policies*: subsidies, taxes,

Vehicle independent

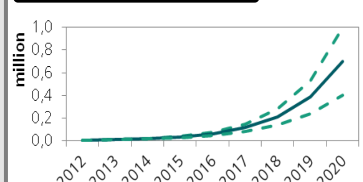
- Fuel/battery/electricity prices until 2020
- Costs for home charging
- Future EV availability

aggregated

Differentiation

- *3 user groups:* private, commercial, company car
- *4 vehicle sizes*: S, M, L, LCV
- *5 technologies*: BEV, PHEV, REEV, gasoline, diesel

Stock model



Projection of:

- Vehicle stock
- Primary charging points stock
- Sales in user group

Car market

- Registrations in user group and vehicle size class
- Stock & sales parameters
- Future availability of EVs

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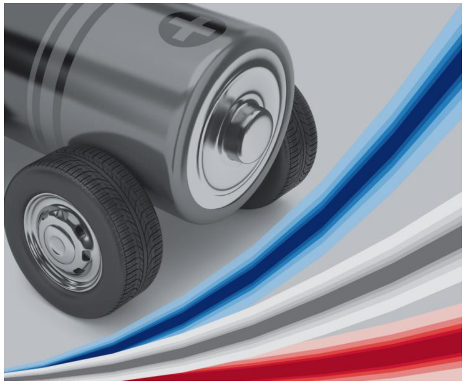

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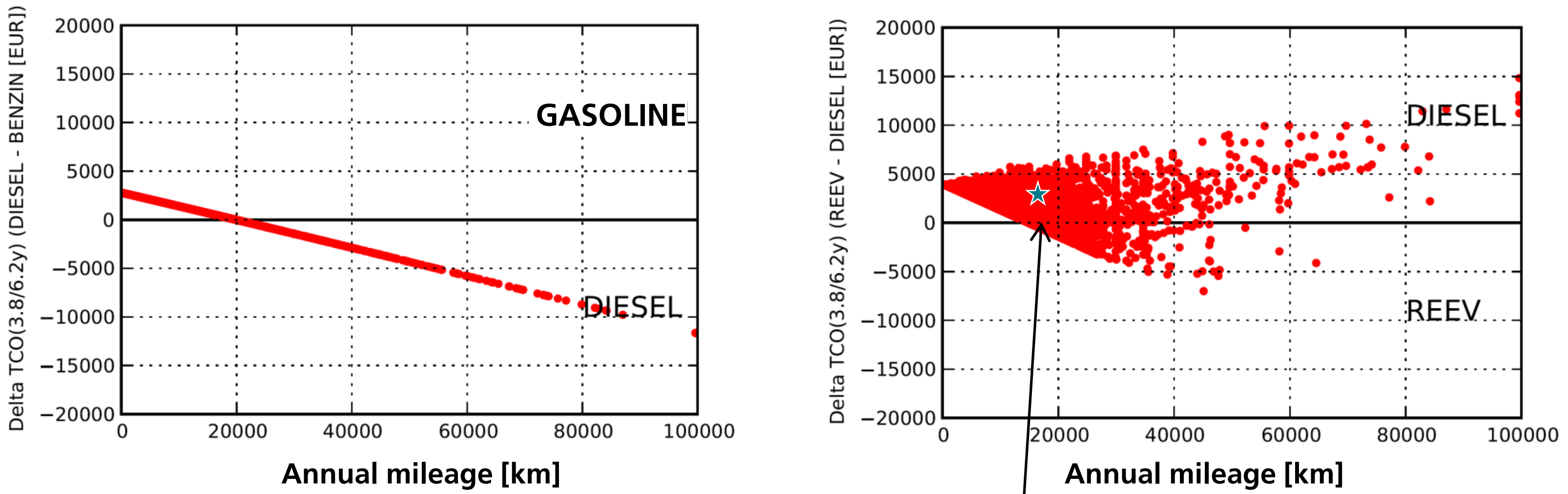
TCO-Results:
There are users with a positive TCO gap.

TCO-difference between gasoline and diesel (left panel) or diesel and REEV (right panel) in 2020 (mid size private car, without infrastructure costs and willingness-to-pay-more):



- Each dot represents an individual vehicle use pattern (★ – other models)
- Diesel vehicles are financially more attractive than gasoline vehicles at a high VKT
- REEV will become economically attractive for certain users in 2020.
- ➢ **Electric vehicles will be economically attractive in some areas in 2020.**

Source: ALADIN (2013_04_26) – Ip1Ig1SmOpt000), medium-sized cars 2020.

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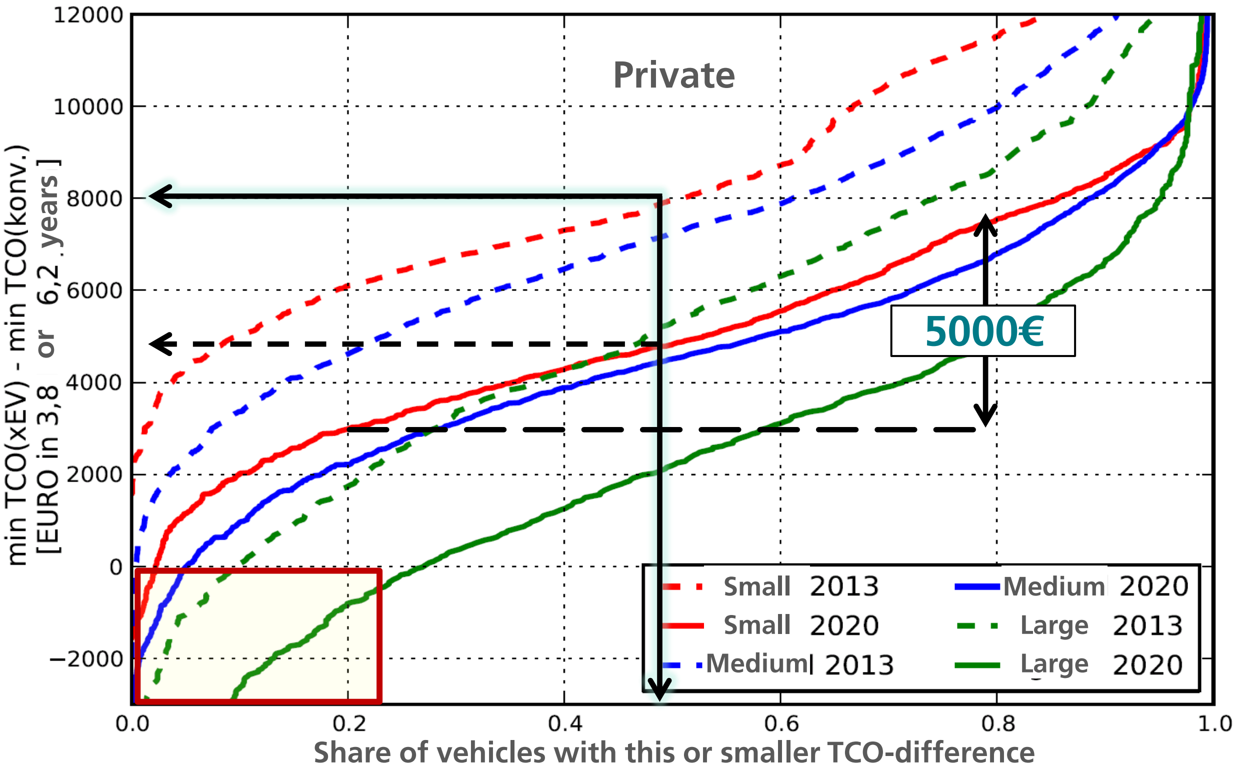
TCO results: EVs will become cost effective for some private users by 2020.

Comparison of cheapest electric and conventional option:

The individual TCO differences between the cheapest electric and conventional option are arranged in ascending order and shown as a function of the share of users with this or smaller TCO difference.



- TCO incl. cost for home charging infrastructure and willingness-to-pay-more
- TCO gaps for full holding time (private: 6.2 years)
- Broad range of TCO gaps, depending on driving distances and behavior
- Negative TCO gap means that EV has lower TCO

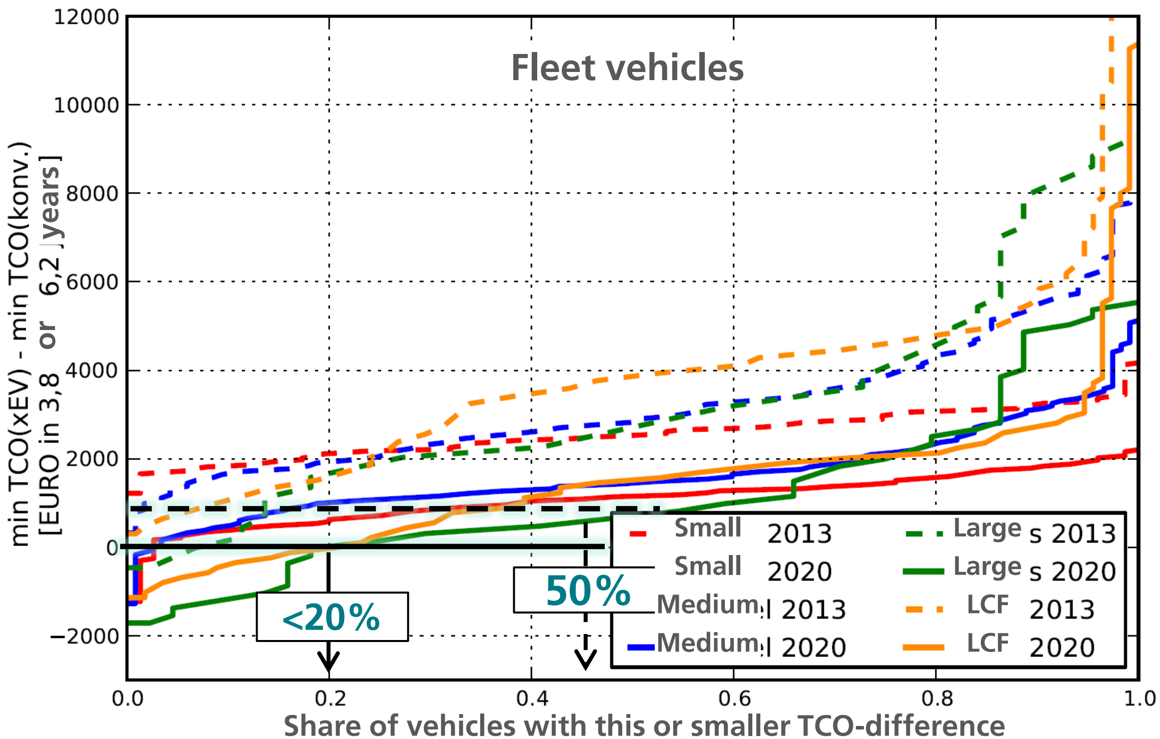
Annual registrations

Car size	Private
Small	486,600
Medium	710,800
Large	146,700

Source: ALADIN (2013_04_26) – Ip1Ig1SmOpt111), private.

TCO results:
TCO gaps close quicker for fleet vehicles.

TCO-Differences for **fleet vehicles** in 2013 and 2020 in middle scenario incl. cost for infrastructure, limited availability and willingness for additional payment:



- Distribution of TCO gaps very flat for fleet vehicles
- Conventional vehicle and EV often very close
- Reasons are depreciation, VAT and high electric driving shares because of more regular and fewer long trips

Annual registrations:

Vehicle size	Fleet vehicles
Small	238.800
Medium	465.800
Large	47.400
LCV	204.000

➢ **Potential leverage: Small effort but large effect.**

Source: ALADIN (2013_04_26) – Ip1lg1SmOpt111), Fleet vehicles.

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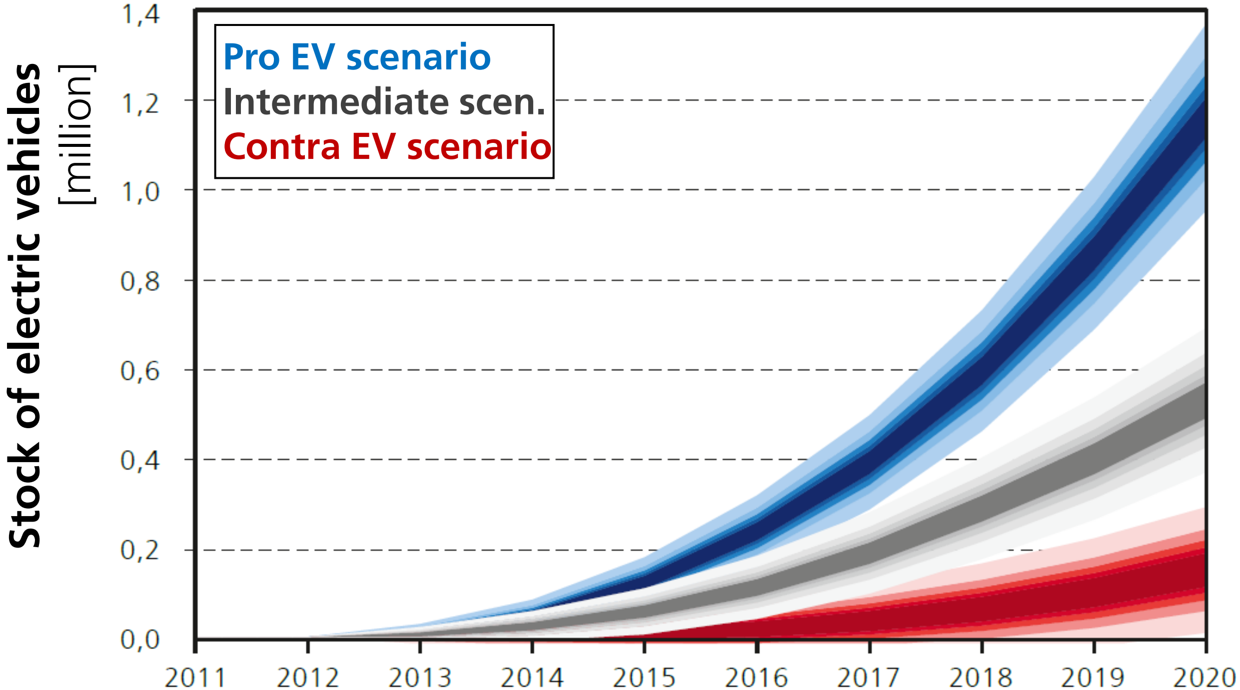
Market diffusion:
External conditions are highly important.

Stock evolution EVs in Germany incl. Cost for primary charging point, limited availability and willingness-to-pay-more in the three scenarios:



Shaded areas show the stock projection with confidence bands from the finite sample size with 10%, 30%, 50%, 70% and 90% confidence level.

Confidence bands are Clopper Pearson with gaussian error propagation.

2020 Scenario	Gasoline price *Euro/Liter*	Electricity private *Euro/kWh*	Electricity industry *Euro/kWh*	Battery price *Euro/kWh*
Pro	1,79	0,29	0,215	300
Intermed.	1,65	0,29	0,215	335
Contra	1,54	0,33	0,25	370

➢ **External conditions have high impact.**

Confidence bands quantify uncertainty only due to finite sample size. Uncertainties concerning future prices or high willingness to pay are not included. Source: Plötz et al (2013) – ALADIN (2013_04_26) – IP1IG1Sm/p/cOpt111).

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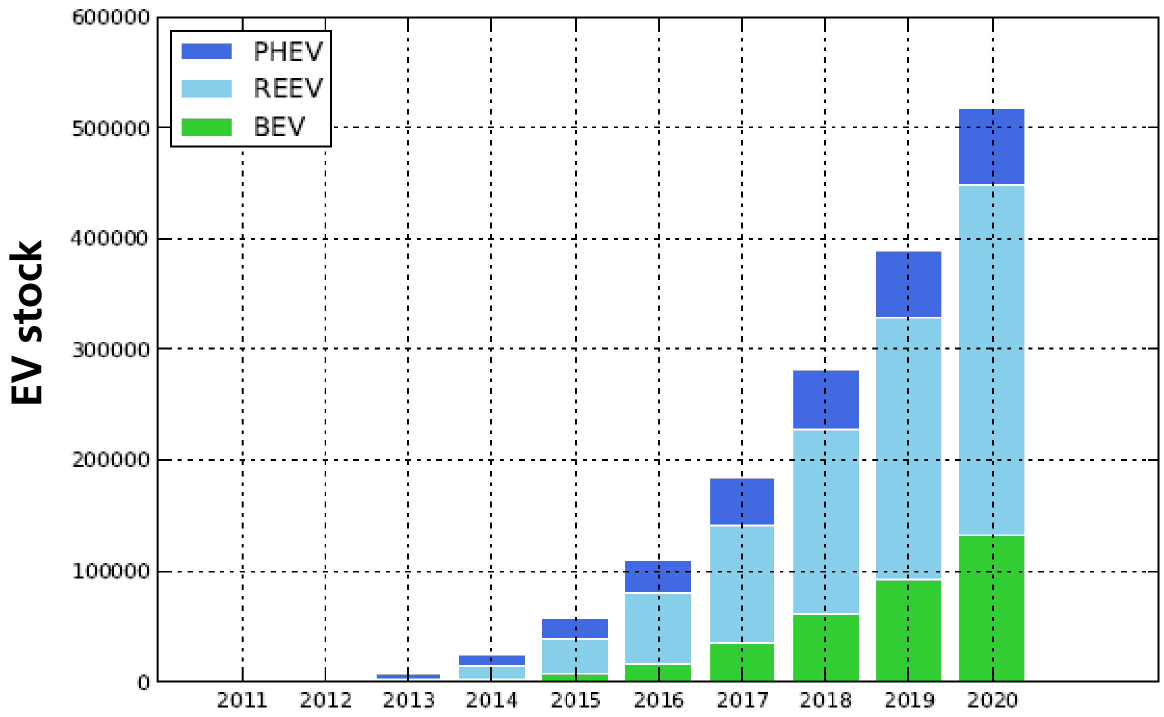
Market diffusion: Plug-in Hybrids will dominate electric vehicle sales.

Market diffusion according to TCO in intermediate scenario:



➢ **Mainly hybrid vehicles (PHEV and REEV) are favored.**

Source: ALADIN (2013_04_26) – Ip1Ig1SmOpt111.

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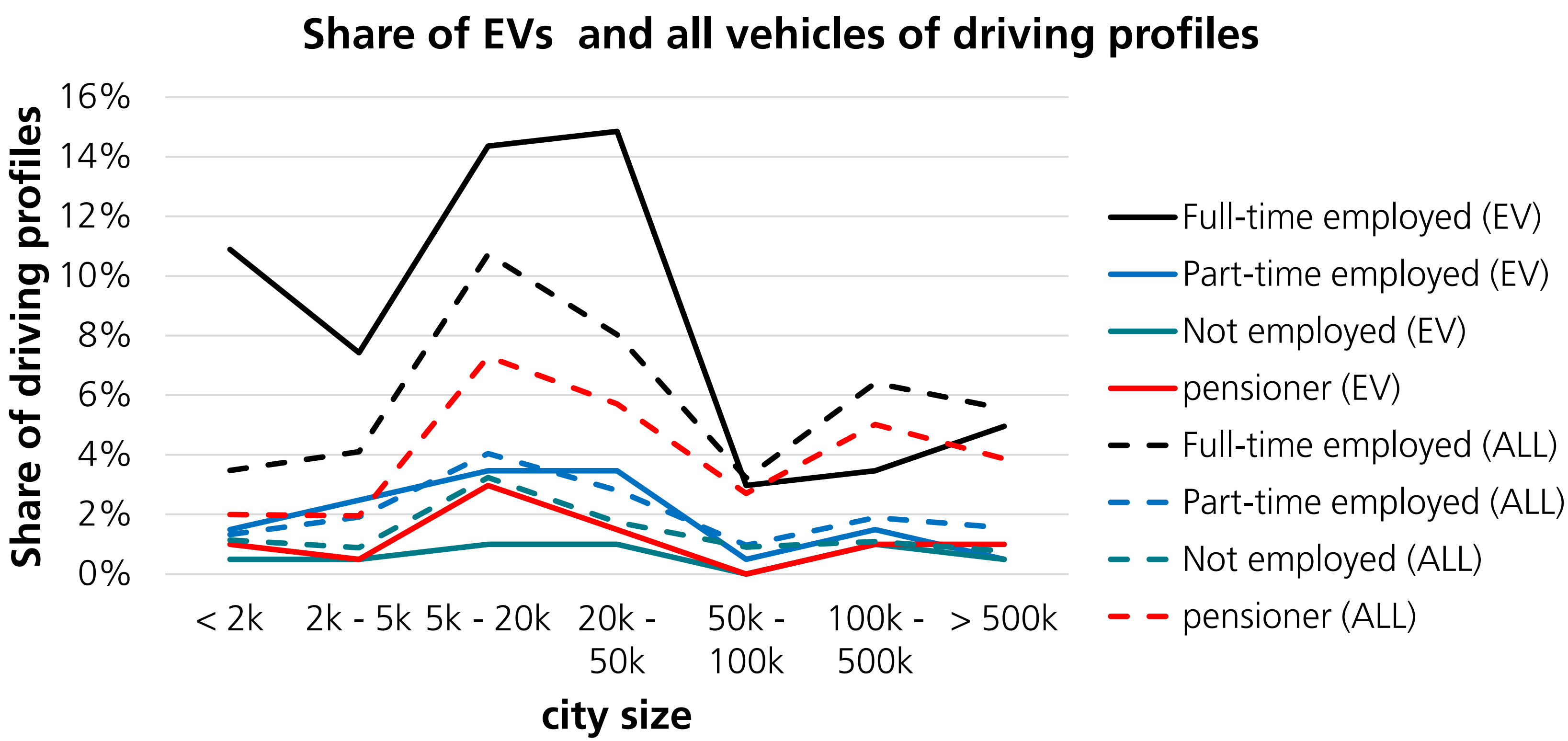
Market diffusion: Early adopter are full-time employees in small to medium sized cities.



- **Early adopter do not live in big cities** (at least for Germany) .
- Psychological results for Germany arrive at similar conclusion (Plötz et al., 2013)

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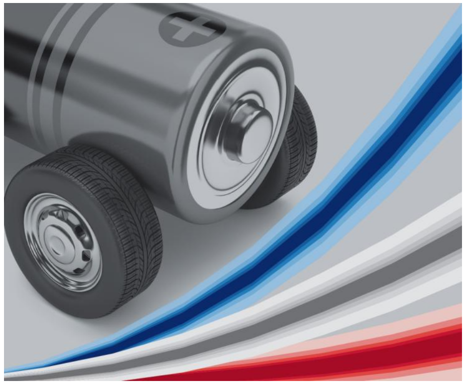

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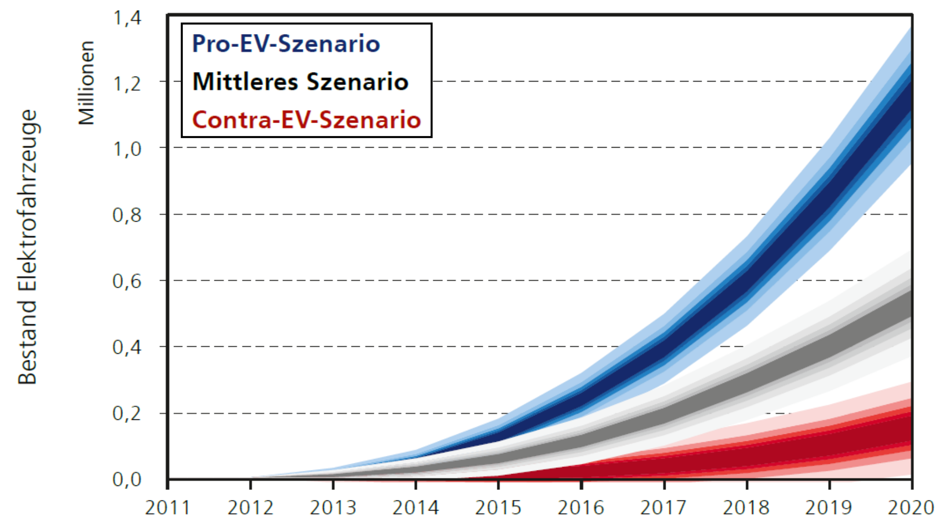
Summary

1. Results of market diffusion demonstrate **great uncertainty** regarding the **PEV market diffusion**, because of:
   - external framework conditions such as price developments for batteries, crude oil and electricity prices,
   - non-monetary factors, e.g. the willingness to pay more for a new technology



2. The most promising groups for PEV adoption are:
   - Commercial **fleet** vehicles (followed by private PEVs and lastly company cars)
   - **PHEVs** before BEVs
   - full-time employees in small to medium sized cities
3. **One million PEVs by 2020 possible** under favorable conditions without monetary support.
   - …**at least that was the case three years ago…**

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Discussion and outlook

Methods and data

New market diffusion model

+ several thousand real-world driving profiles
+ integration of home-charging and soft factors

Statistical analysis

+ Large data base allows statistical tests for significance and robustness of results

Need more data!

- Limited number of driving profiles from company cars and commercial fleets.

Observation time could be longer

- Variety in daily vehicle use of individual requires longer observation of driving behaviour (cf. Pearre et al. 2011, Smith et al. 2011, Karlsson & Kullingsjö 2013)

Future research

Buying decision for company cars

Buying decision for company cars is involved with different actors and not yet understood

Public charging infrastructure

Impact of public charging options on buying decision not completely clear

Connection to theory

Connection to discrete choice methods and utility maximisation needs to be formulated more precisely (cf. Train 2009)

Competition with other technologies

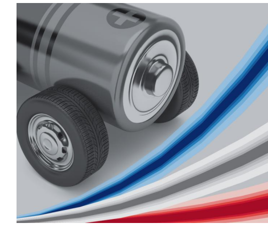
include FCEVs and CNG vehicles as well as other user groups (e.g. Car sharing)

Buying decisions are complex

Willingness to pay and limited availability difficult to estimate and anticipate.
PHEV/BEV distinction difficult to model

References: Pearre, N. S. et al. (2011): Electric vehicles: How much range is required for a day's driving? *Transportation Research Part C*, 19 (6), 1171–1184. Smith, R. et al. (2011): Characterization of urban commuter driving profiles to optimize battery size in light-duty plug-in Electric Vehicles. *Transportation Research Part D* 16 (3), 218–224 . Karlsson, S. & Kullingsjö, L.-H. (2013): GPS measurement of Swedish car movements for assessment of possible electrification. *EVS 27*, Barcelona. Train, K. (2009) *Discrete Choice Methods and Simulation.*

Thank you for your attention!



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Further information:

Plötz, P; Gnann, T.; Wietschel, M. (2014): Modelling market diffusion of electric vehicles with real world driving data — Part I: Model structure and validation Elsevier, Ecological Economics Vol 107, Nov 2014, pages 411-421

Gnann, T.; Plötz, P.; Kühn, A.; Wietschel, M. (2015): Modelling Market Diffusion of Electric Vehicles with Real World Driving Data – German market and Policy options. Transportation Research Part A, Vol. 77, July 2015, pp. 95-112