3rd International Workshop on Empirical Methods in Energy Economics (EMEE2010)

Surrey Energy Economics Centre (SEEC)

University of Surrey, UK

24th – 25th June 2010

NOTE:

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fcn Institute for Future Energy Consumer Needs and Behavior

RWTH AACHEN UNIVERSITY

Assessing the Power Sector-Related Environmental and Cost Impacts of Plug-in Hybrid Electric Vehicles in Germany

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3rd International Workshop on Empirical Methods
in Energy Economics (EMEE 2010)
SEEC, University of Surrey, 24-25 June 2010

June 8th, 2010

Overview

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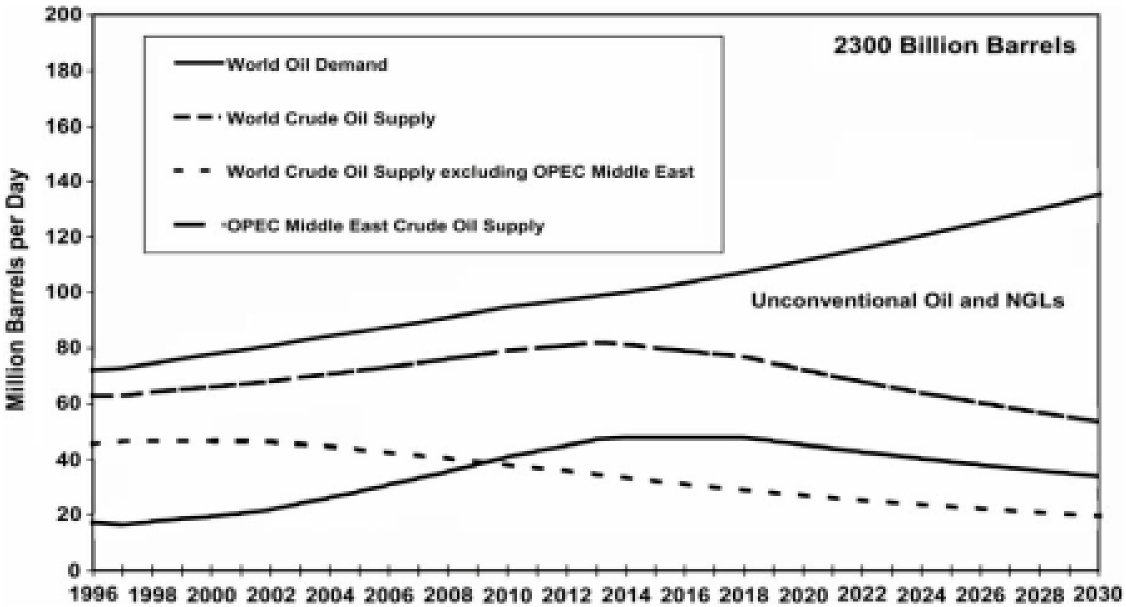
- Introduction
- Related Literature
- Aim and Scope of our Work
- Methodology
- Results and Findings
- Conclusions

Overview

- Introduction
  - Current Challenges in Mobility
  - Electric Mobility and V2G
  - Electricity Market
  - PHEV: A Challenge and an Opportunity for Electricity Producers
- State-of-the-Art
- Aim and Scope of our Work
- Methodology
- Results and Findings
- Conclusions

Introduction: Current Challenges in Mobility



(Van Mierlo et al., 2006)

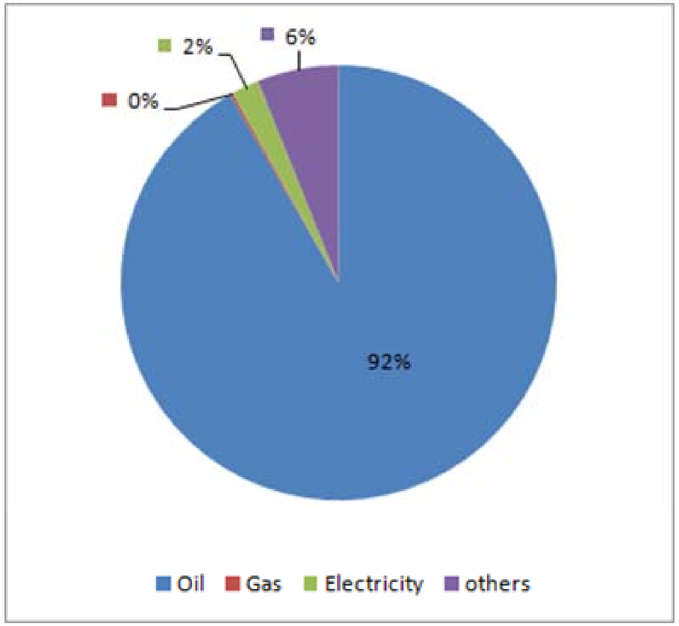


Figure 1: Energy sources in transportation for Germany

Source: (BMWi, 2007)

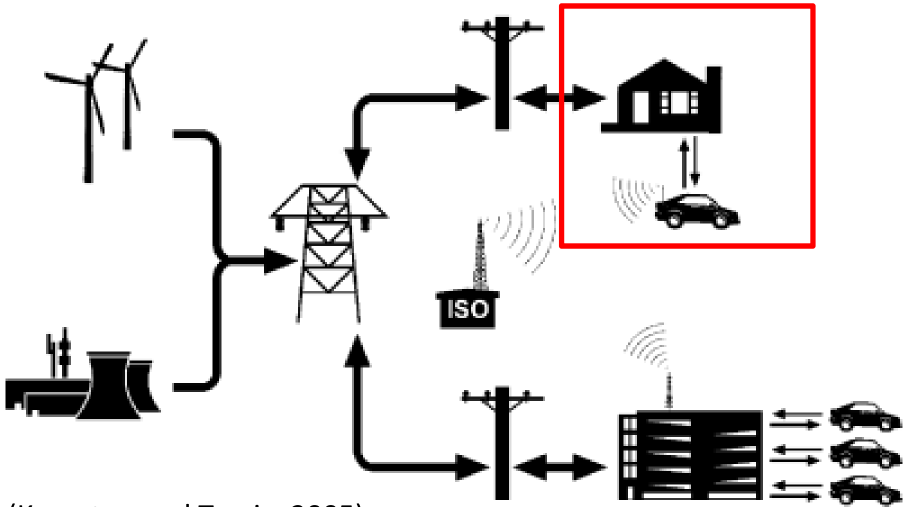
- High dependency on crude oil
- Peak oil
- Greenhouse gas emissions / Global warming
  - ca. 18% of total CO_2 in Germany
- Urban air pollution

→ Electric Mobility

Introduction: Electric Mobility and V2G

- Battery Electric Vehicle (BEV)
- Hybrid Electric Vehicle (HEV)
- Plug-in Hybrid Electric Vehicles (PHEV)
- PVEV, FCV, etc.

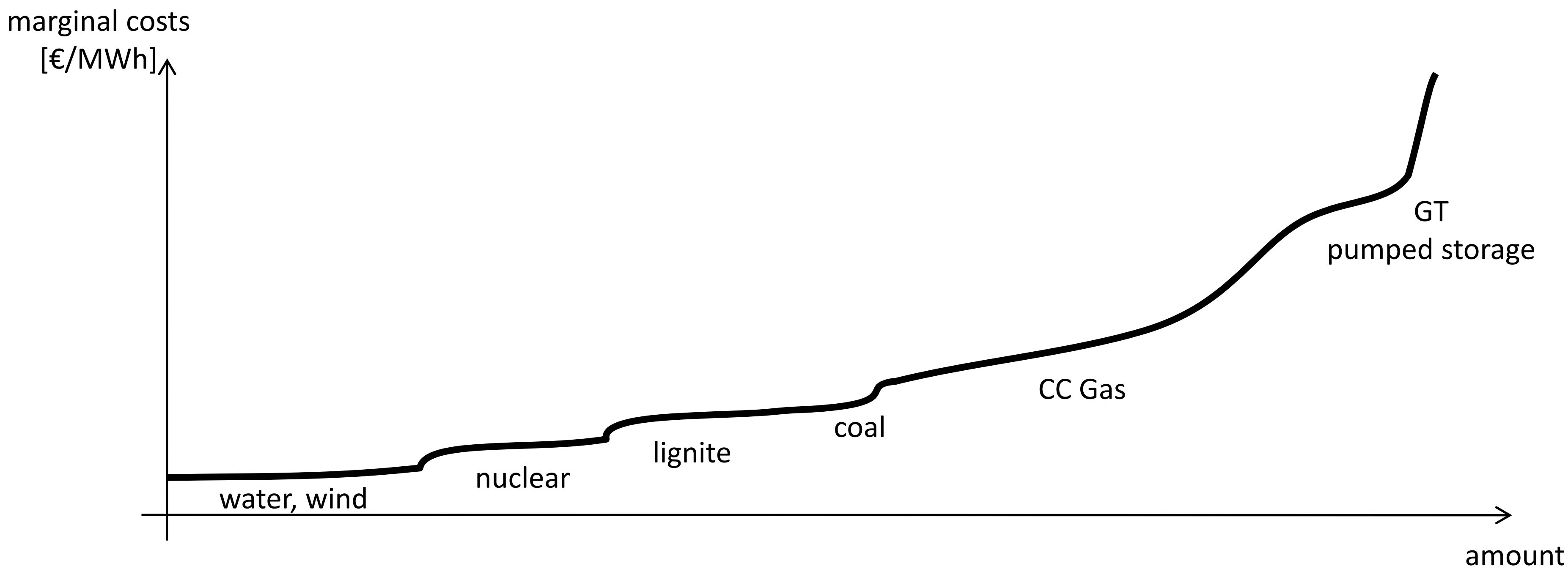
- Vehicle-to-Grid (V2G)
  - Discharging energy stored in battery to the grid



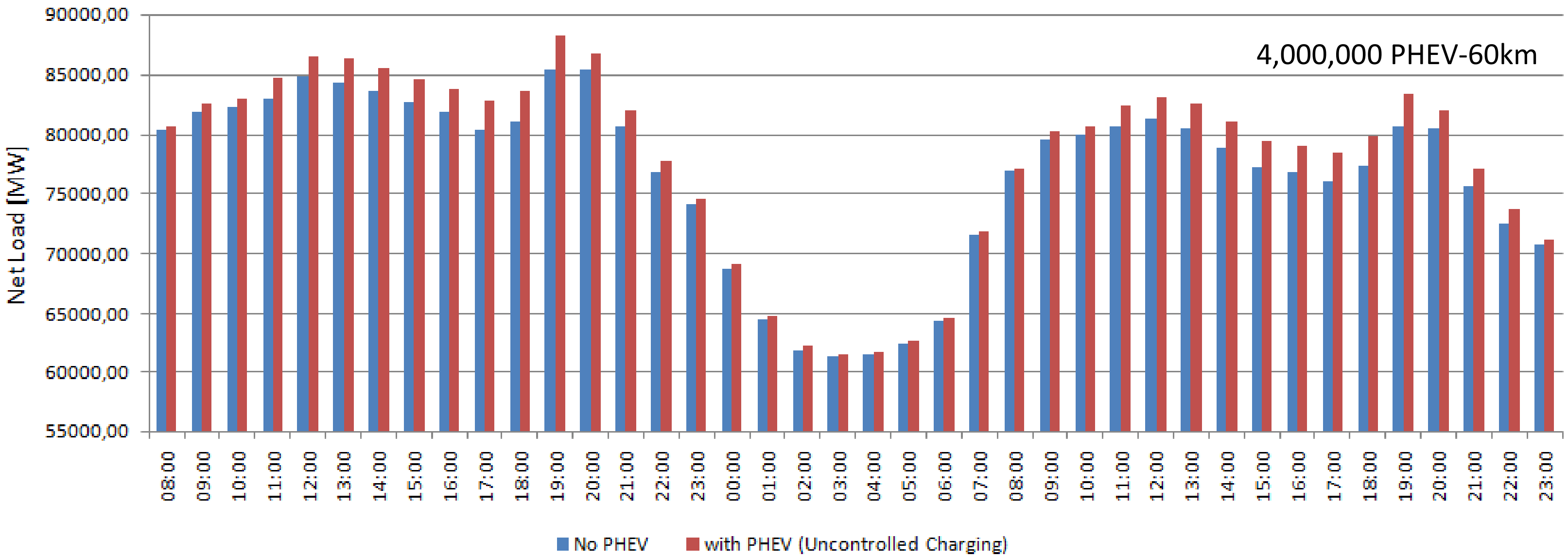
(Kempton and Tomic, 2005)

Introduction: Electricity Market

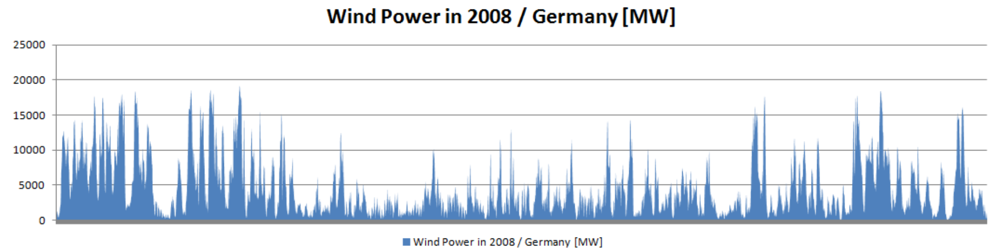
- Electricity market characteristics
  - Demand = Supply!
  - High volatility of the demand (seasonal, daily)
  - Hardly any storage
    - 7,000 MW (MWh/h) load and 40,000 MWh storage in Germany
  - Base-load and peaking plants



PHEV: A Challenge and an Opportunity for Electricity Producers



- Controlled Charging / Morning Charging
  - Prevent PHEV loading during peak hours
  - Move loading to hours of low electricity demand
- Vehicle-to-Grid
  - Use of PHEV energy in peak hours
  - Replace peaking plants
  - Storage of excess energy (e.g. wind?)



4,000,000 PHEV-60km (12 kWh) → 12,000 MW load
48,000 MWh storage

Overview

Related Literature (on Daily load impacts of PHEVs)

- Short and Denholm (2006)
- Kintner-Meyer, Schneider and Pratt (2007) – focus North America, generation mix 2002; into of PHEV-33, "load valley-filling" approach
- Parks, Denholm and Markel (2007) – Off-peak charging optimizing grid utilization at off-peak times (control by the SO)
- Fernandez et al. (2009) – Spain, 2030, dumb vs smart charging (+V2G)
- Sioshansi (2009), Sioshansi and Denholm (2009ab); Texas
- Rotering and Ilic (2009) – Fast charging maximizing electric energy charged/use of the electric drive; Smart charging that maximizes profit from V2G
- Clement, Haesen and Driesen (2009) – Uncontrolled charging with delay to minimize electricity cost; Controlled charging minimizing power losses in the distribution grid

State-of-the-Art (1/3)

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Table 2: Impact of V2G on Generation Costs in dependence of PHEV penetration

PHEV Penetration	Generation Costs ($)		Value of V2G ($)
	With V2G	Without V2G	
0%	n/a	34,133,080	n/a
1%	34,117,191	34,153,689	36,498
5%	34,199,011	34,299,564	100,553
10%	34,353,691	34,492,594	138,903
15%	34,534,952	34,690,096	155,144

Source: Sioshansi and Denholm (2009a)

- Controlled Charging leads to lower generation costs

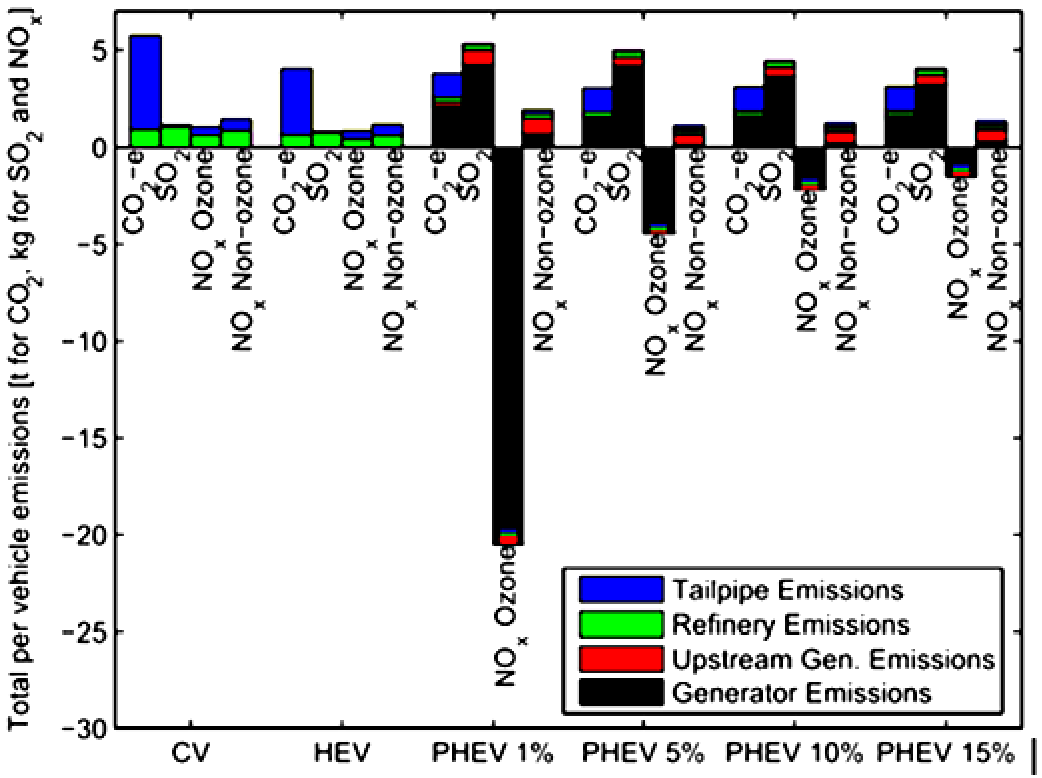

Figure 10: Impact of Controlled Charging and V2G on vehicle emissions

Source: Sioshansi and Denholm (2009a)

- Effects of Controlled Charging depend on electricity generation system
- PHEVs reduce GHG emissions at the tailpipe
- Sioshansi and Denholm (2009):
  - Texas
  - Coal-fired plants with poor SO_2 treatment

State-of-the-Art (3/3)

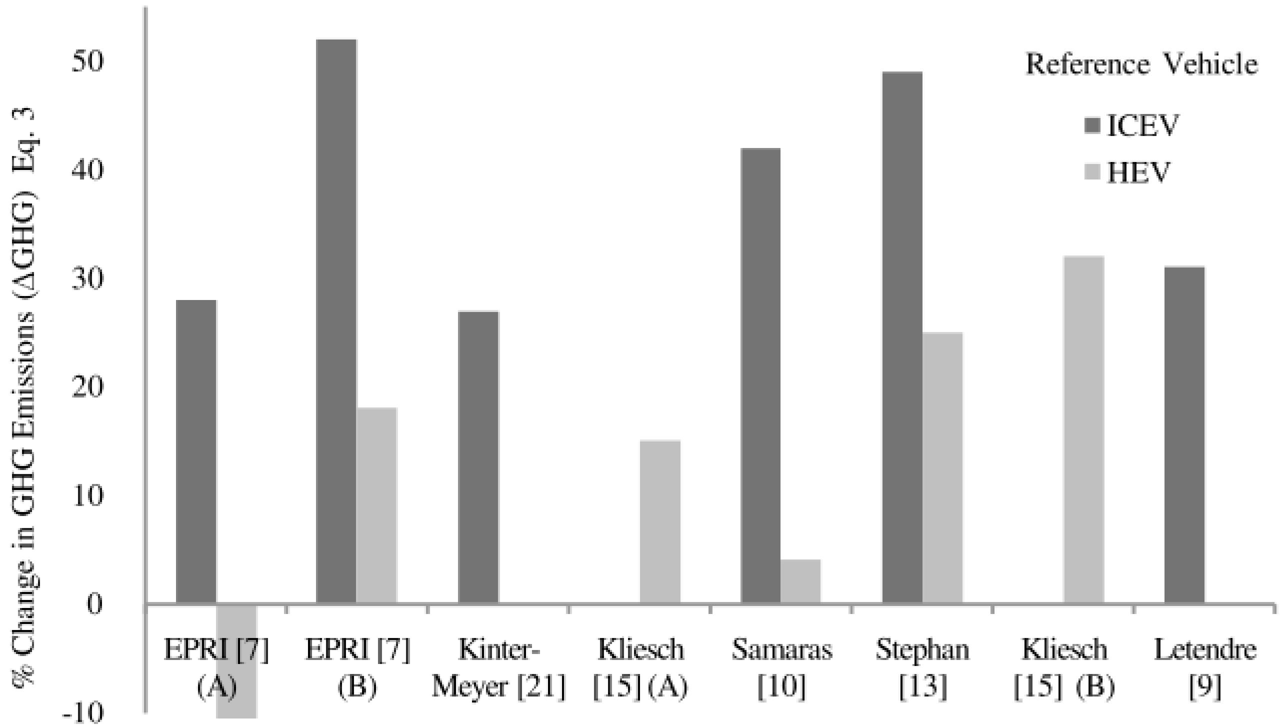

Figure 9: Overview over results in literature concerning emissions and penetration
Dowds et al. 2009

- Power from the electrical grid requires additional power generation and causes additional GHG emissions from the electrical sector.

Overview

Aim and Scope of our Work

- Focus of our study: Germany

- What is the annual impact of PHEVs …
  - … on the daily load in Germany?
  - … on generators deployment in Germany?
  - … on generation costs in Germany?
  - … on GHG and pollutant emissions in Germany?

- What is the influence of different charging scenarios, for instance Uncontrolled Charging, Morning Charging or V2G?

- What is the effect of different energy mixes?
  - Current energy mix
  - After nuclear power phase out
  - 'French' energy mix

- How are PHEV owners affected?
  - … in terms of fuel costs

Overview

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- Introduction
- Related Literature
- Aim and Scope of our Work
- Methodology
  - The Model
  - Activity Diagram of Matlab Code
  - Charging Scenarios / Control over Charging
- Results and Findings
- Conclusions

The Model

Modeling and Simulating the Impact of Plug-in Hybrid Electric Vehicles and V2G on Electricity Generation Costs and Emissions

Modeling and Simulation of Power Generation Infrastructure

- Real world power plant data
- Real world net load curve
- Real world wind power production
- UC model based on Sioshansi (2009)
- Data for 2008

Modeling and Simulation of Vehicle Usage Pattern

- Determination of PHEV connected to grid and energy stored in batteries (based on Hartmann et al. (2009)
- Different Charging Scenarios
- 'Mobility in Deutschland' study (DIW 2003)
- Data for 2001

Simulation with Matlab/lp_solve

Impact

- Power generation costs
- Generation emissions
- PHEV emissions
- PHEV 'fuel' costs
- Power plant deployment

The Model

$$\min \sum_{i \in I} \left(S_i s_{Q,t} + SP_i u_{i,t} + c_i q_{i,t} + CI_i inc_{i,t} + CD_i dec_{i,t} \right)$$

S … start-up costs; SP … spinning costs; CI, CD … marg. cost of increasing/decreasing power gen.

s.t. $$\sum_{i \in I} q_{i,t} = l_t + p_t$$ Load balance (supply = demand)

$$0 \le q_{i,t} \le MQ_{i,t}$$ Max. output (global gen. restrictions)

$$-R_i \le q_{i,t} - q_{i,t-1} \le R_i$$ Generation flexibility (gradient of load change)

$$\sum_{\tau = t - gd_i}^{t} h_{i,t} \le 1 - u_{i,t}$$ Minimum up-time

$$\sum_{\tau = t - gu_i}^{t} s_{i,t} \le u_{i,t}$$ Minimum down-time

$$u_{i,t} - s_{i,t} + h_{i,t} = u_{i,t-1}$$ $$u_{i,t}, s_{i,t}, h_{i,t} \in \{0,1\}$$

UML Activity Diagram

Illustration of Matlab Program

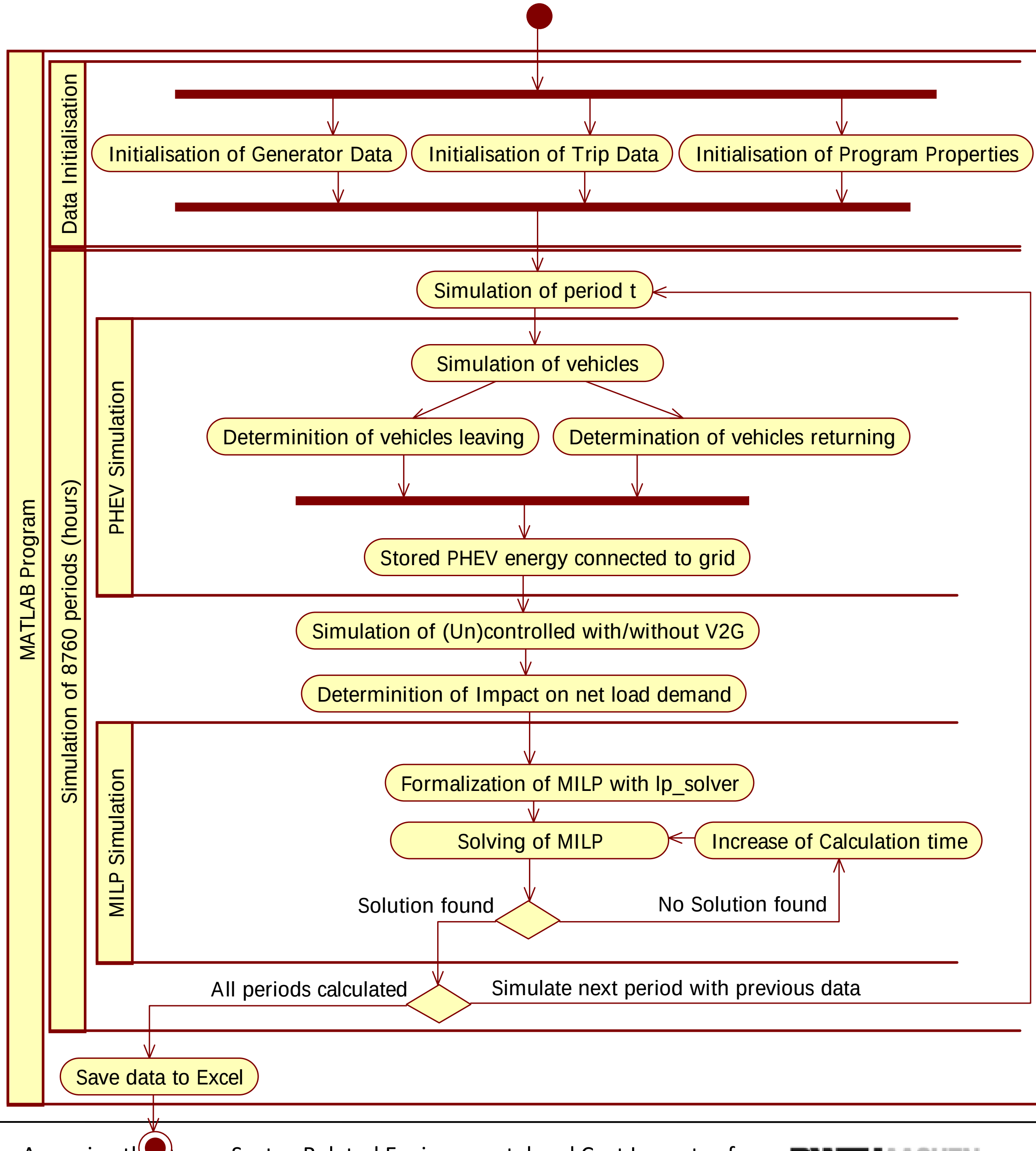
<u>Scenarios</u>
•400,000 / 2,000,000 / 4,000,000 PHEVs
•PHEV-30km / PHEV-60km

<u>Charging Scenarios / Controlled Charging</u>
•No PHEV
•Uncontrolled Charging
•Morning Charging
•Morning Charging + V2G

<u>8760 periods p. a. / 24 cases</u>

<u>linear function</u> f(x) to be maximized with 1638 variables
and
<u>problem constraint</u> Ax=b with 1912 constraints

3 hours of simulation per year and scenario



Charging Scenarios (1/2)

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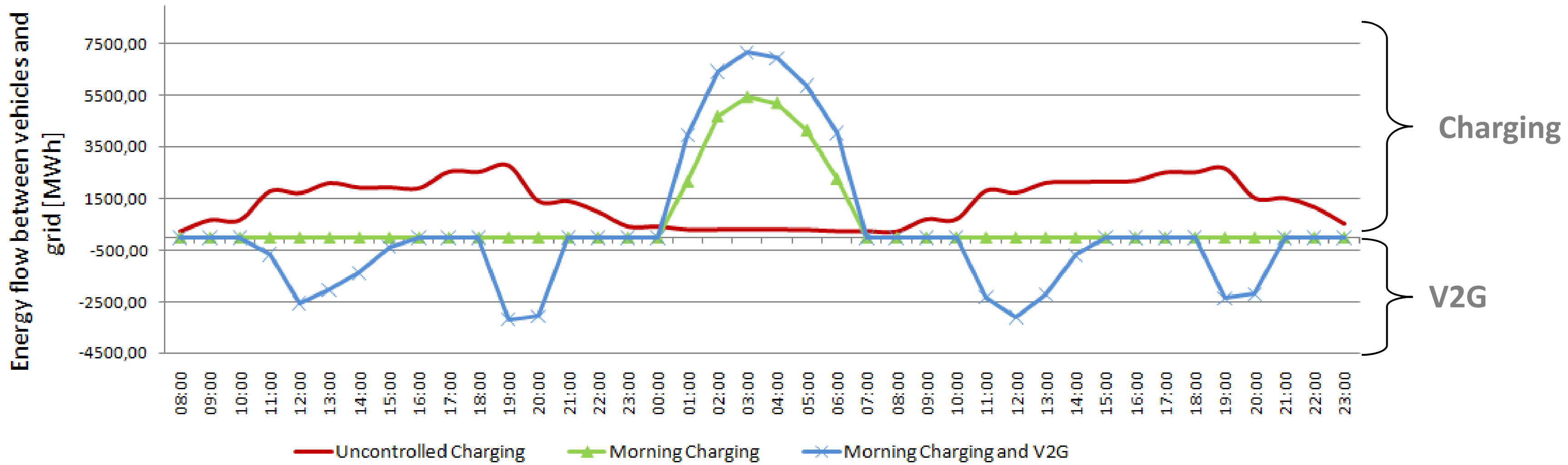

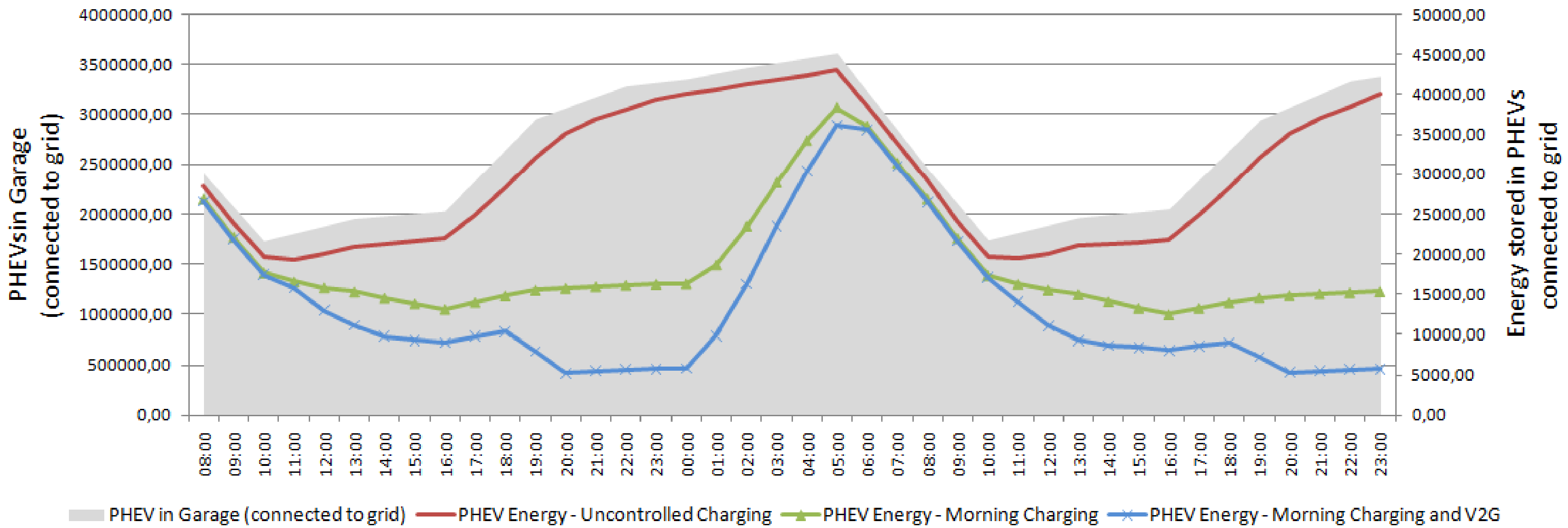

4,000,000 PHEV-60km

Charging Scenarios (2/2)

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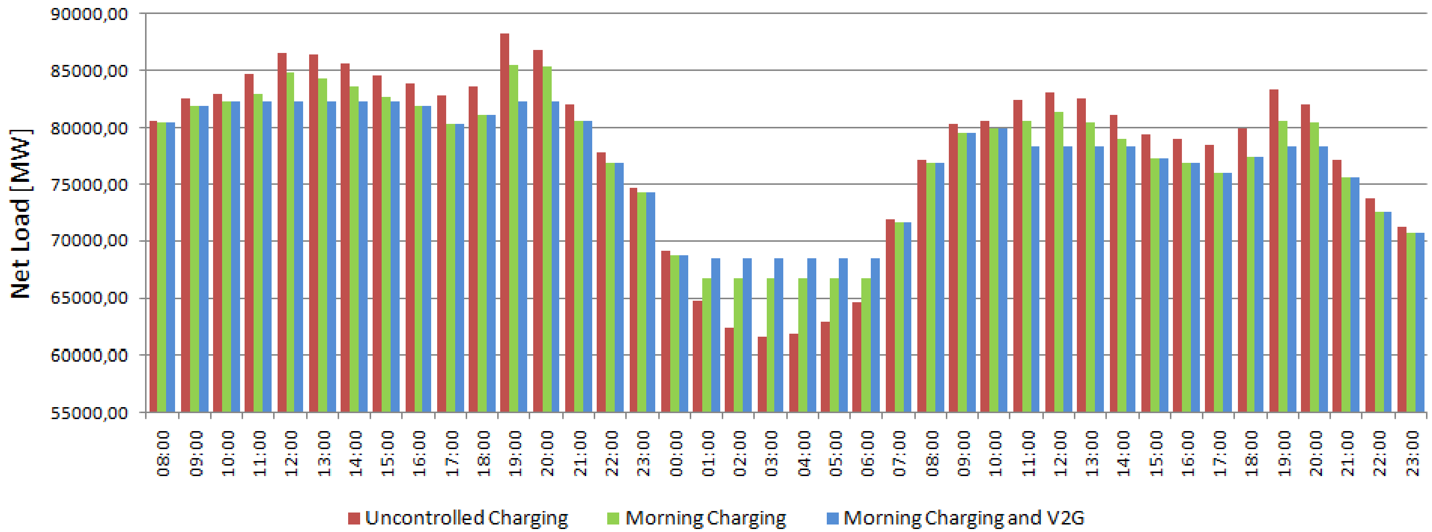

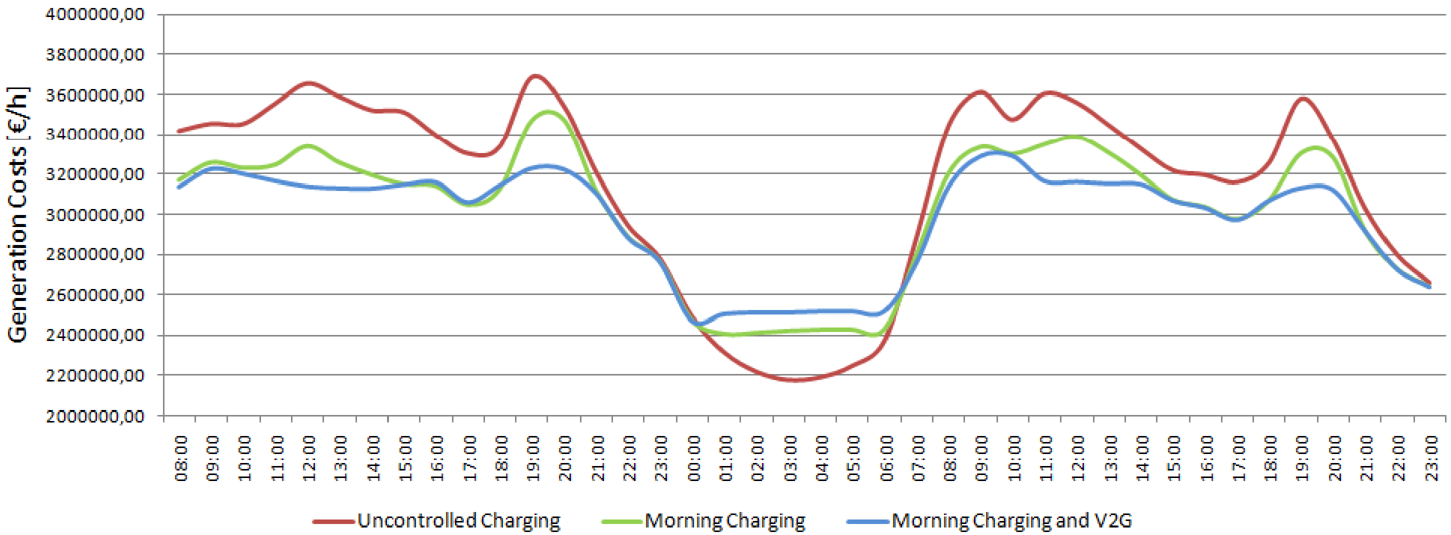

4,000,000 PHEV-60km

Overview

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- Related Literature
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- Methodology
- Results and Findings
  - Generator Deployment
  - Generation Costs and Emissions
  - PHEV Costs and Emissions
  - Impact of Other Energy Mixes
- Conclusions

Generator Deployment

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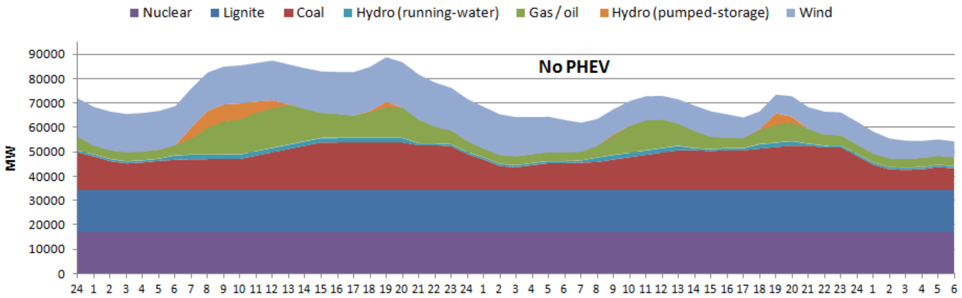

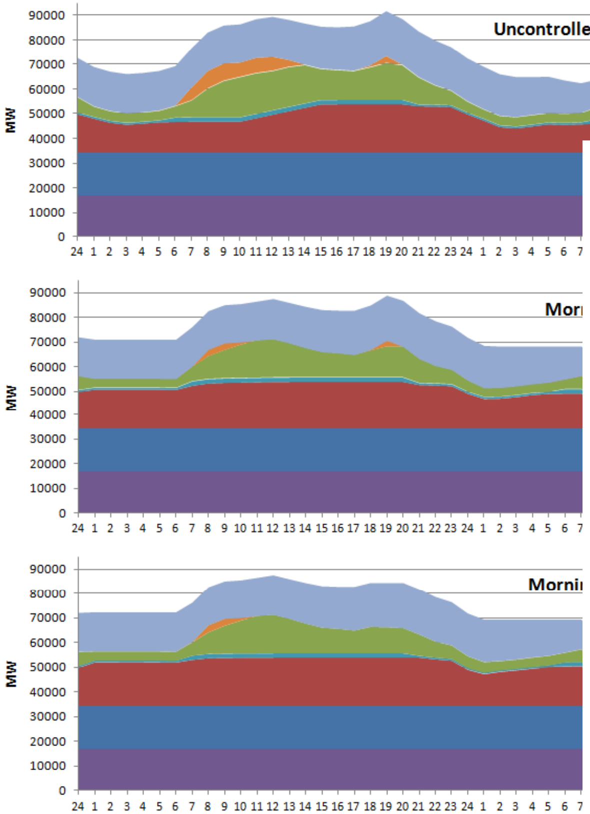

With Controlled Charging

- Lower deployment of peaking plants
- Higher deployment of coal fired plants

Table 20: Deployment of generator types depending on charging scenario in comparison to case where no PHEVs exist (4,000,000 PHEV-60km)

	Deployment of generator types						
Charging Scenario	Basic Scenario (No PHEVs)	Uncontrolled Charging		Morning Charging		Morning Charging and V2G	
Generator Type	Distribution of total output	Distribution total output	Change in total output	Distribution total output	Change in total output	Distribution total output	Change in total output
Lignite	26.1 %	25.7 %	0 %	25.7 %	0 %	25.8 %	0 %
Nuclear	25.5 %	25.1 %	0 %	25.2 %	0 %	25.2 %	0 %
Coal	21.7 %	21.8 %	+1.9 %	24.1 %	+12.5 %	25.1 %	+16.9 %
Gas / Oil	14.9 %	15.4 %	+4.5 %	13.7 %	-6.6 %	13.2 %	-10.7 %
Hydro (running water)	2.2 %	2.1 %	+0.1 %	2.1 %	-1.7 %	2.1 %	-0.8 %
Hydro (pump-storage)	2.9 %	3.2 %	+14.8 %	2.4 %	- 13.6 %	1.9 %	-33.5 %
Wind Power	6.7 %	6.7 %	+0.2 %	6.7 %	+1.4 %	6.7 %	+1.3 %

Source: own simulation

Generation Costs and Emissions

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Table 19: Generation cost and emission depending on charging control and PHEV diffusion

Charging Scenario / Penetration		Power generation cost [€/MWh] No PHEVs	Uncontrolled Charging	Morning Charging	Morning Charging and V2G
No PHEVs	0 %	38.40	-	-	-
PHEV-30km	400,000 (1%)	-	38.43	38.31	38.29
	2,000,000 (5%)	-	38.54	38.18	38.12
	4,000,000 (10%)	-	38.69	38.03	37.89
PHEV-60km	400,000 (1%)	-	38.44	38.30	38.22
	2,000,000 (5%)	-	38.58	38.10	37.81
	4,000,000 (10%)	-	38.75	37.88	37.49

Source: own calculations

With Controlled Charging

- Generation costs ⬇
- Average Emissions ⬆

Table 21: Impact of PHEV diffusion and charging scenario on average electricity generation emission

Result / Penetration		Uncontrolled Charging CO_2 kg/MWh	Uncontrolled Charging SO_2 g/MWh	Uncontrolled Charging NO_x g/MWh	Morning Charging CO_2 kg/MWh	Morning Charging SO_2 g/MWh	Morning Charging NO_x g/MWh	Morning Charging and V2G CO_2 kg/MWh	Morning Charging and V2G SO_2 g/MWh	Morning Charging and V2G NO_x g/MWh
No PHEVs	0	612	404	563	-	-	-	-	-	-
PHEV-30km	400,000	612	404	563	613	406	563	613	406	563
	2,000,000	612	404	564	616	410	565	617	411	565
	4,000,000	612	403	565	620	415	567	621	418	567
PHEV-60km	400,000	612	404	563	613	406	563	615	408	563
	2,000,000	612	403	564	618	413	566	622	418	567
	4,000,000	612	403	564	622	419	568	627	425	569

(Average emission per 1 MWh electricity generation output)

Source: own simulation

PHEV Operation Modes

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Table 24: Average annual ratio of driven distance in All Electric or CS Mode depending on PHEV type and control over charging

	Average annual ratio between All Electric and CS mode of PHEV					
	Uncontrolled Charging		Morning Charging		Morning Charging and V2G	
	All Electric	CS Mode	All Electric	CS Mode	All Electric	CS Mode
PHEV-30km	61 %	39 %	48 %	52 %	45 %	55 %
PHEV-60km	77 %	23 %	70 %	30 %	64 %	36 %

Source: own simulation

With Controlled Charging:

- Not only the specific emission footprint of the energy changes, but also ratio of driven kilometers in All-Electric Mode decreases

PHEV Costs

Table 24: Average annual ratio of driven distance in All Electric or CS Mode depending on PHEV type and control over charging

	Average annual ratio between All Electric and CS mode of PHEV					
	Uncontrolled Charging		Morning Charging		Morning Charging and V2G	
	All Electric	CS Mode	All Electric	CS Mode	All Electric	CS Mode
PHEV-30km	61 %	39 %	48 %	52 %	45 %	55 %
PHEV-60km	77 %	23 %	70 %	30 %	64 %	36 %

Source: own simulation

Table 27: Annual fuel cost of PHEV in regard to range and charging scenario

For comparison:
Conventional vehicle
€1368 p.a. and 14,481 km

	Average annual fuel cost for 14480 km (electricity and petrol)		
	Uncontrolled Charging	Morning Charging	Morning Charging and V2G
	Annual Fuel Cost € / a	Annual Fuel Cost € / a	Annual Fuel Cost € / a
PHEV-30km	780	849	863
PHEV-60km	696	731	766

Source: own simulation

With Controlled Charging: Fuel costs increase

4,000,000 PHEV-60km

PHEV Emissions

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Table 24: Average annual ratio of driven distance in All Electric or CS Mode depending on PHEV type and control over charging

	Average annual ratio between All Electric and CS mode of PHEV					
	Uncontrolled Charging		Morning Charging		Morning Charging and V2G	
	All Electric	CS Mode	All Electric	CS Mode	All Electric	CS Mode
PHEV-30km	61 %	39 %	48 %	52 %	45 %	55 %
PHEV-60km	77 %	23 %	70 %	30 %	64 %	36 %

Source: own simulation

Table 25: PHEV emissions per kilometer depending on diffusion and control over charging

	Result / Penetration	Average PHEV emission per 1 km								
		Uncontrolled Charging			Morning Charging			Morning Charging and V2G		
		CO_2 g/km	SO_2 mg/km	NO_x mg/km	CO_2 g/km	SO_2 mg/km	NO_x mg/km	CO_2 g/km	SO_2 mg/km	NO_x mg/km
PHEV-30km	400,000	131.1	55.6	162.2	134.2	47.0	179.4	134.9	45.2	183.1
	2,000,000	131.1	55.5	162.3	134.5	47.4	179.5	135.2	45.7	183.0
	4,000,000	131.1	55.4	162.4	134.9	48.0	179.6	135.6	46.4	183.1
PHEV-60km	400,000	127.5	66.1	141.5	129.2	62.0	150.3	130.8	57.8	158.8
	2,000,000	127.4	66.0	141.6	129.8	62.9	150.6	131.7	59.5	158.6
	4,000,000	127.4	66.0	141.8	130.5	63.8	150.9	132.4	60.1	159.5

Source: own simulation

With Controlled Charging: Average vehicle emissions increase

PHEV Emissions

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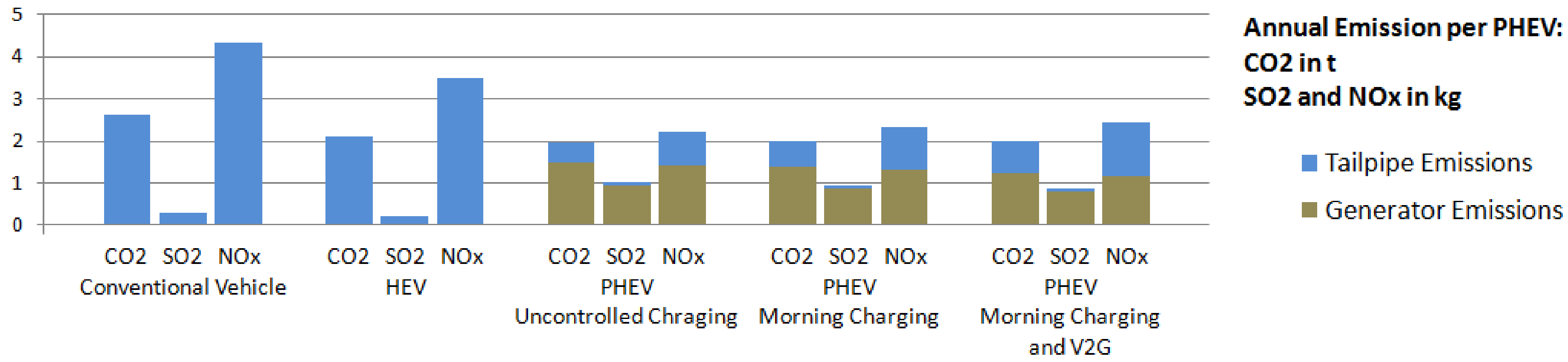
- Annual per-vehicle emissions in t per year and average travel distance of 14,481 km
  - PHEV-60km
  - Current energy mix



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Impact of Other Energy Mixes (1/3)

- Germany in 2020 with nuclear power phased out

Table 31: Impact of phasing out of nuclear power in Germany on generator emission (year 2020)
4,000,000 PHEV-60kms

	Average emission per 1 MWh electricity generation output								
	Uncontrolled Charging			Morning Charging			Morning Charging and V2G		
	CO_2 kg/MWh	SO_2 g/MWh	NO_x g/MWh	CO_2 kg/MWh	SO_2 g/MWh	NO_x g/MWh	CO_2 kg/MWh	SO_2 g/MWh	NO_x g/MWh
Current German energy mix	611	403	565	622	419	568	627	425	569
German energy mix in 2020 without nuclear power	670	423	638	674	428	639	674	428	639

Source: own simulation

Table 32: Impact of phasing out of nuclear power in Germany on PHEV emission (year 2020)
4,000,000 PHEV-60kms

	Average PHEV emission per kilometer								
	Uncontrolled Charging			Morning Charging			Morning Charging and V2G		
	CO_2 g/km	SO_2 mg/km	NO_x mg/km	CO_2 g/km	SO_2 mg/km	NO_x mg/km	CO_2 g/km	SO_2 mg/km	NO_x mg/km
Current German energy mix	127.4	66.0	141.8	130.5	63.8	150.9	132.4	60.1	159.5
German energy mix in 2020 without nuclear power	136.5	69.1	153.0	137.7	65.1	160.9	138.4	60.5	168.4

Source: own simulation

Impact of Other Energy Mixes (2/3)

- Germany in 2020 with 'French' energy mix

Table 35: Impact of high nuclear power diffusion on generator emission (French energy mix) 4,000,000 PHEV-60kms

	Average emission per 1 MWh electricity generation output								
	Uncontrolled Charging			Morning Charging			Morning Charging and V2G		
	CO_2 kg/MWh	SO_2 g/MWh	NO_x g/MWh	CO_2 kg/MWh	SO_2 g/MWh	NO_x g/MWh	CO_2 kg/MWh	SO_2 g/MWh	NO_x g/MWh
Current German energy mix	611	403	565	622	419	568	627	425	569
Germany with French energy mix	107	131	207	114	140	210	116	144	210

Source: own simulation

Table 36: Impact of high nuclear power diffusion on PHEV emission (French energy mix) 4,000,000 PHEV-60kms

	Average PHEV emission per kilometer								
	Uncontrolled Charging			Morning Charging			Morning Charging and V2G		
	CO_2 g/km	SO_2 mg/km	NO_x mg/km	CO_2 g/km	SO_2 mg/km	NO_x mg/km	CO_2 g/km	SO_2 mg/km	NO_x mg/km
Current German energy mix	127.4	66.0	141.8	130.5	63.8	150.9	132.4	60.1	159.5
Germany with French energy mix	49.4	23.9	86.3	58.8	24.5	100.4	67.3	24.2	113.6

Source: own simulation

Impact of Other Energy Mixes (3/3)

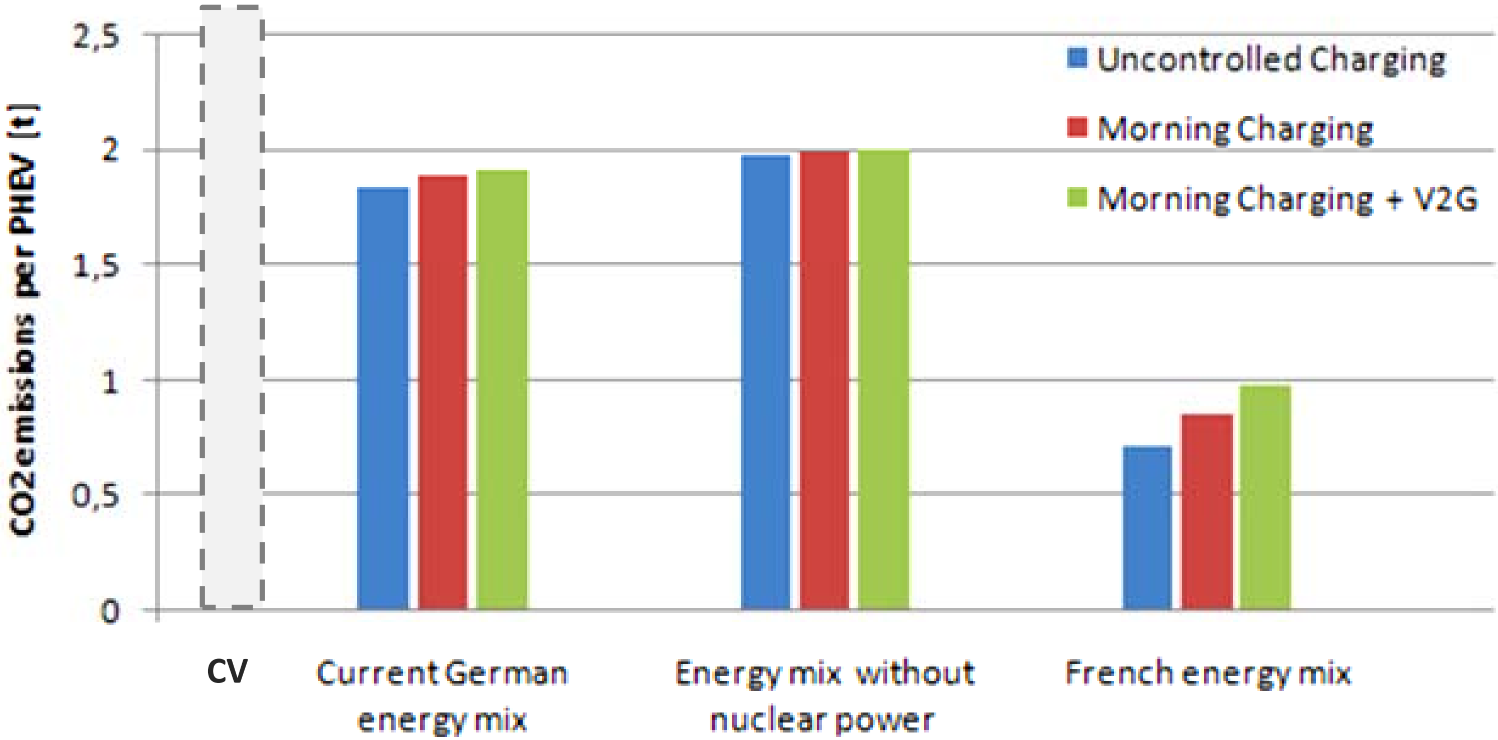

Figure 26: Impact of Charging Control on PHEV CO_2 emissions in regard to energy mix. (Annual average CO_2 emissions per PHEV for 14481 km)

Source: own illustration, based on own simulation

Overview

Conclusions

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- With current energy mix
  - Uncontrolled Charging leads to higher generation costs
  - Incentives for electricity producers to control charging patterns & V2G
    - Decrease of generation costs
    - Increase of generation emissions
    - Increase of PHEV fuel costs and emissions
- Energy mix without nuclear power leads to slightly higher emissions
  - if nuclear power is substituted to a large extent by wind power
- 'French' energy mix is affected the most by controlled charging

- Scope for future research:
  - Modeling of impacts of grid constraints
  - Optimization 24 hours ahead
  - More detailed modeling of power generation system
    - by efficiency factor, age, size of plant etc.
  - Simulation of individual PHEV usage instead of aggregated pools

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Thank you for your attention

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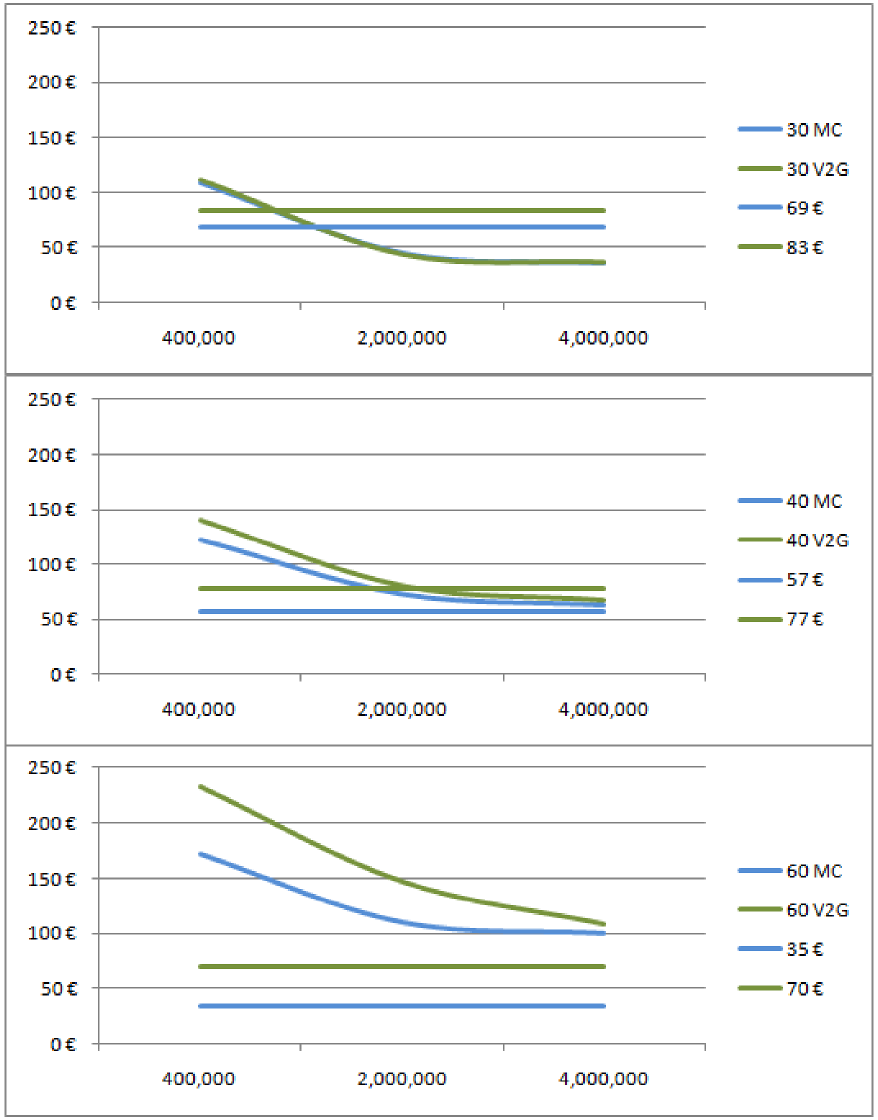
Back-up
slides



		Interval for average annual compensation paid by electricity producers to PHEV owners (per PHEV)			
		Morning Charging		Morning Charging and V2G	
	Penetration	Average annual utility loss for PHEV owner (additional fuel cost)	Average annual utility gain for electricity producer per PHEV	Average annual utility loss for PHEV owner (additional fuel cost)	Average annual utility gain for electricity producer per PHEV
PHEV-30km	400,000	69 €	108 €	83 €	111 €
	2,000,000		45 €		44 €
	4,000,000		36 €		37 €
PHEV-40km	400,000	57 €	123 €	77 €	140 €
	2,000,000		73 €		80 €
	4,000,000		63 €		67 €
PHEV-60km	400,000	35 €	172 €	70 €	233 €
	2,000,000		110 €		147 €
	4,000,000		100 €		108 €

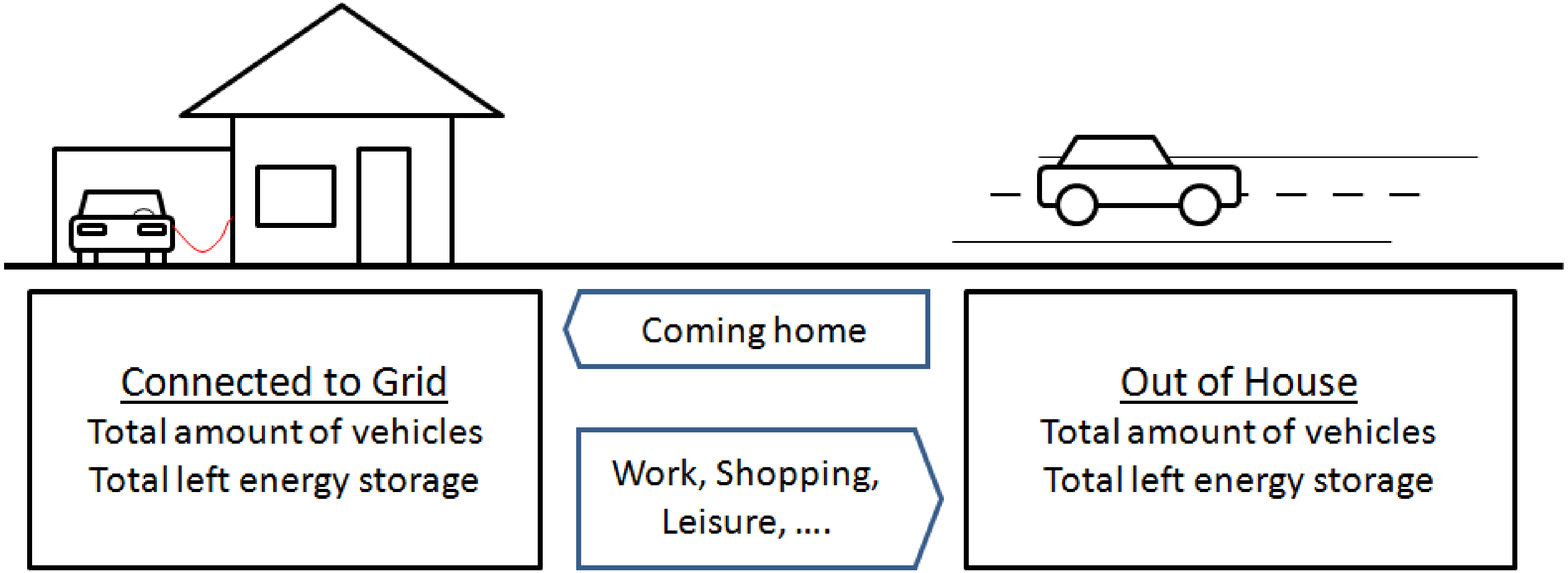


Figure 14: Illustration of modeled PHEV Data. Left: Aggregation of PHEVs at home, connected to grid and their total stored energy. Right: Aggregation of PHEVs out of house and their left stored energy.
Source: own illustration

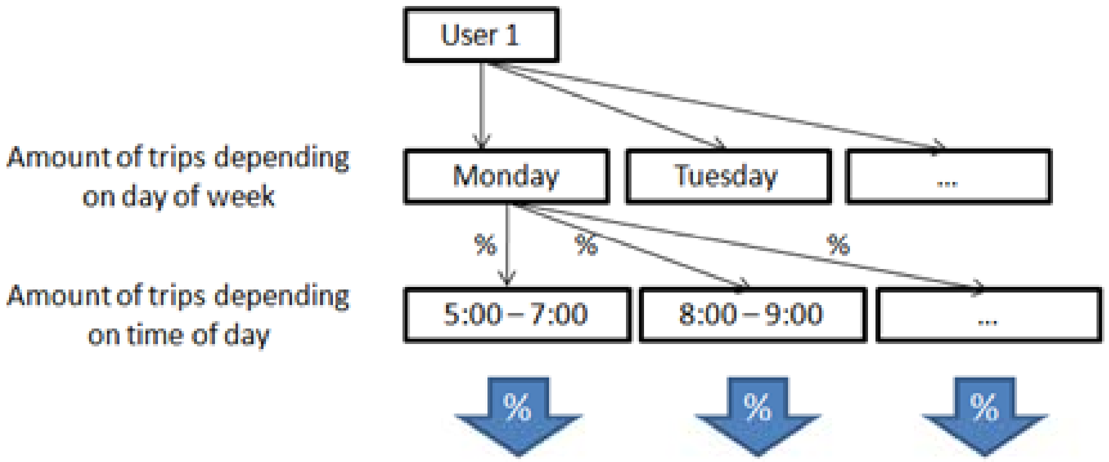


Figure 15: Approach for modeling PHEVs flows
Source: own illustration

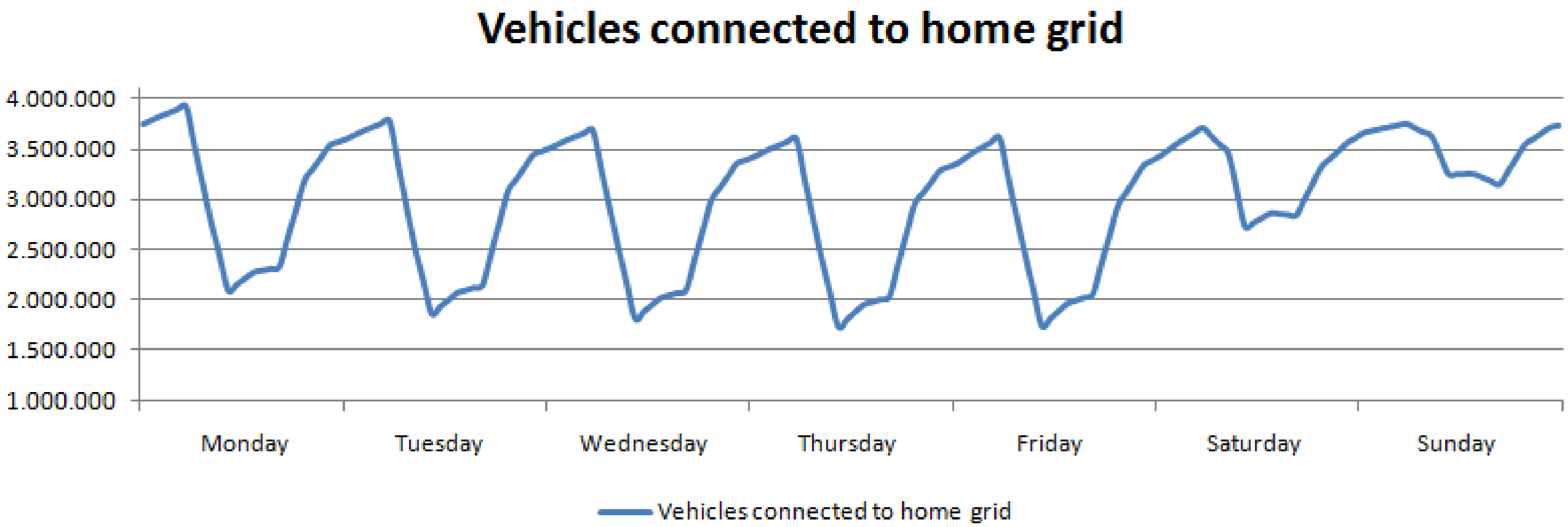


Figure 16: Amount of vehicles connected to home grid (simulated 4,000,000 PHEV-60km)
Source: own illustration, results of own simulation, based on (DIW, 2003)

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Charging Scenarios