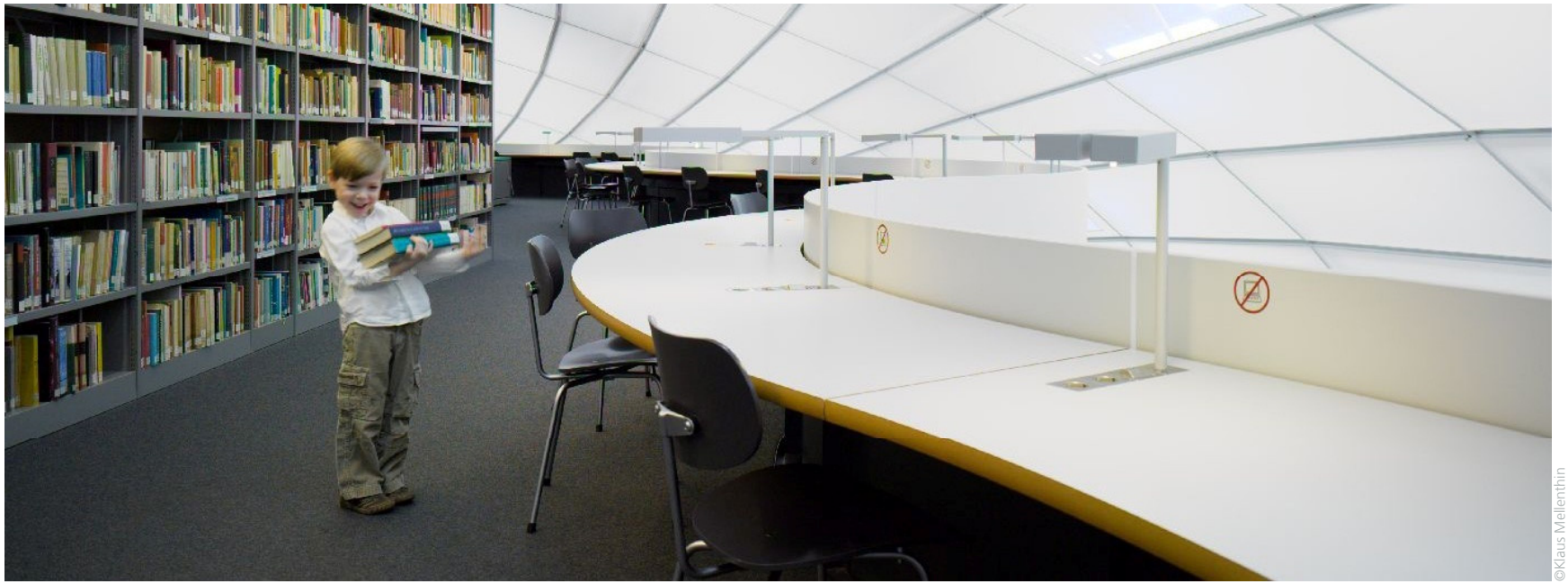
GRID INTEGRATION OF INTERMITTENT RENEWABLE POWER SUPPLY USING PRICE-RESPONSIVE PLUG-IN ELECTRIC VEHICLES

Berkeley, May 2nd 2012



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- Characteristics of fluctuating generation
- Comparing fluctuating generation in CA and GER
- Characteristics of mobile storage
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Characteristics of fluctuating generation

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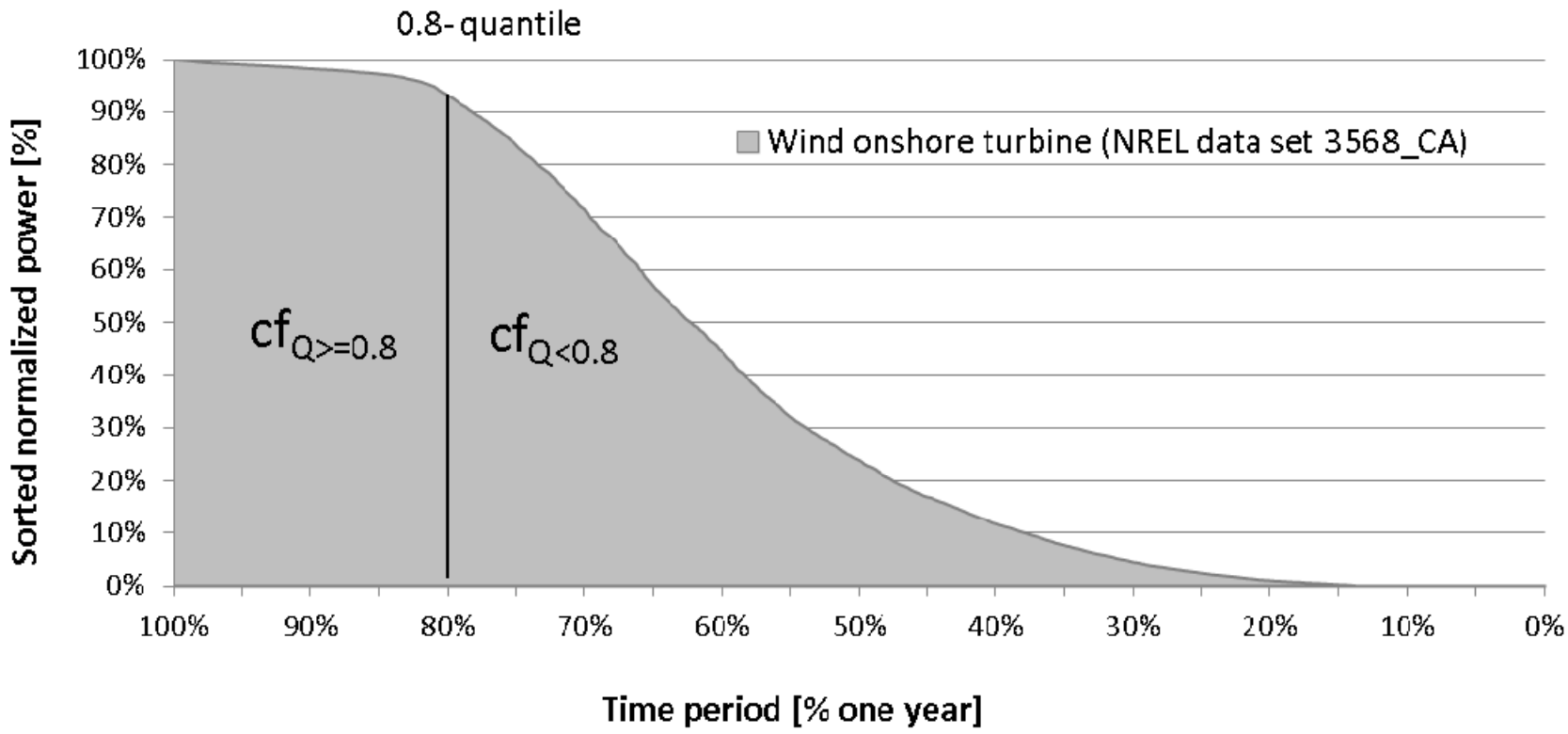
Duration curve

Characteristics of fluctuating generation



Data basis: Time series (NREL, 2009)

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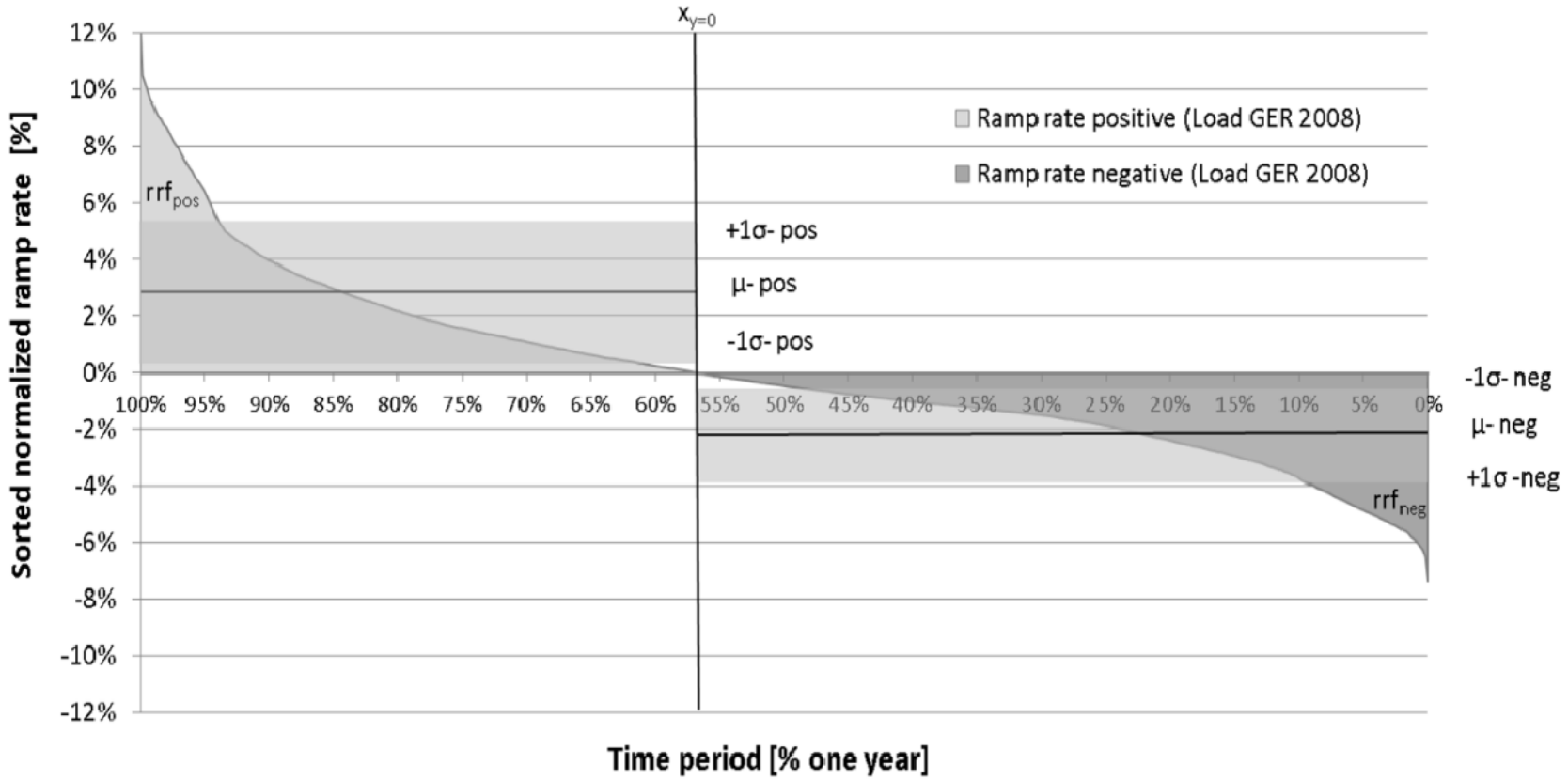
Ramp rates

Characteristics of fluctuating generation



Ramp rate: $rr(t) = \frac{P_{t+1} - P_t}{P_{rated} or P_{peak}}$

Ramp rate factor: $rrf = \sum_t \frac{1}{T}(t_{t-1} - t_t) \cdot (rr_{t+1} + rr_t) \cdot 0.5$

Data basis: GER: Germany ENTSO-E, 2010 reference year 2008

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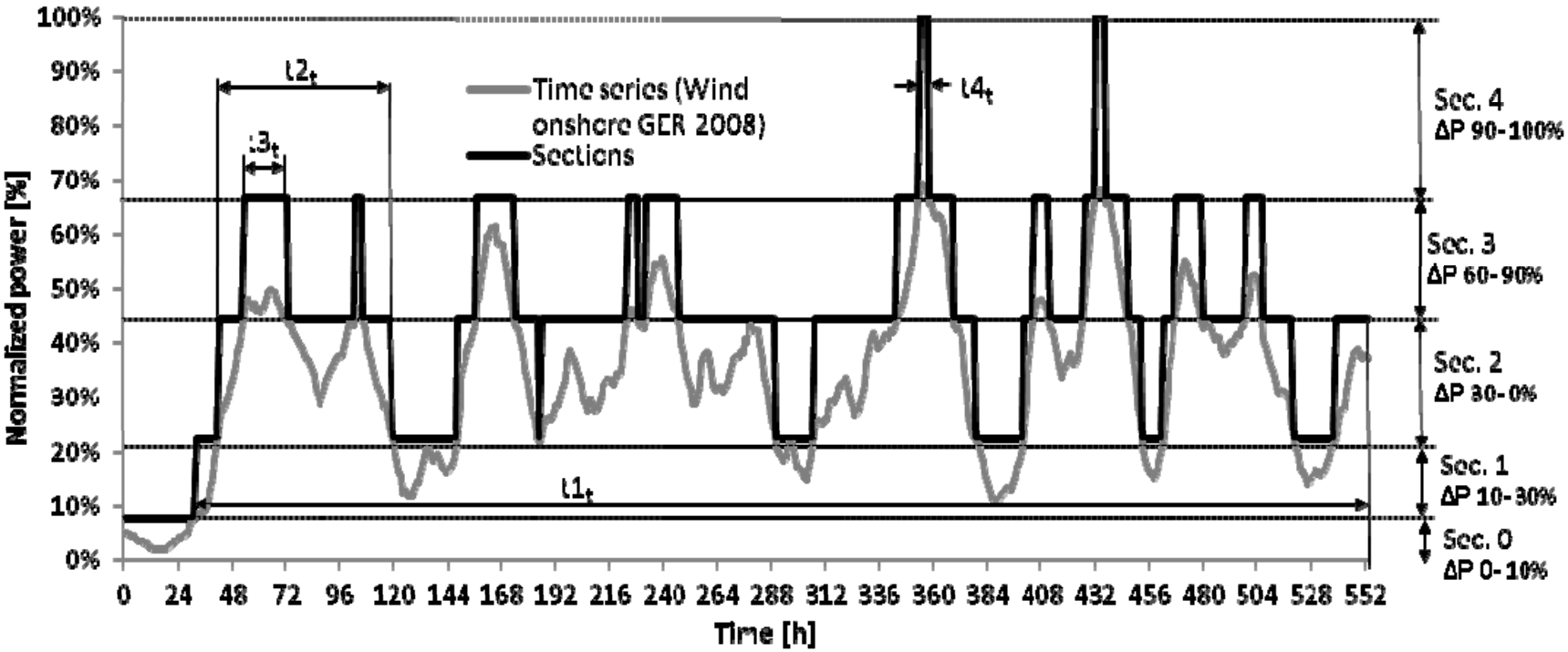
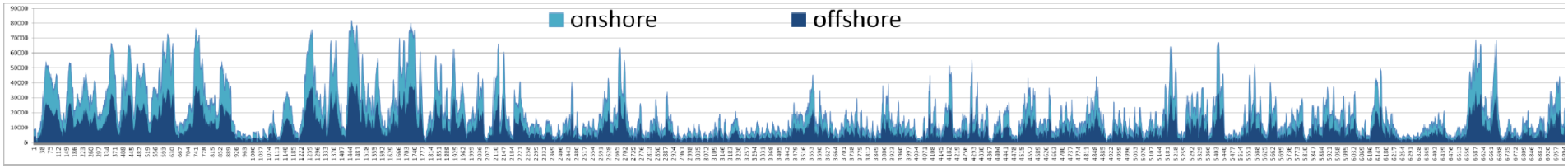
Interval availability

Characteristics of fluctuating generation



Data basis:: EEX, 2011



Comparing fluctuating generation in CA and in GER

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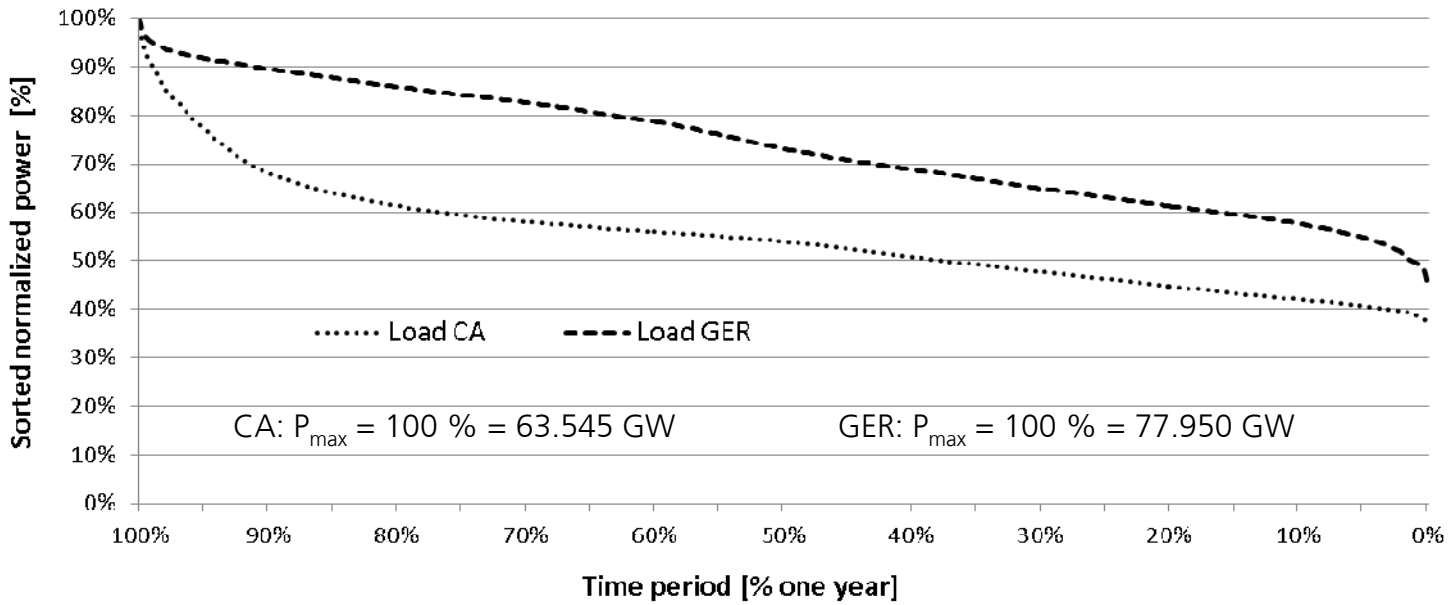
Load curve

CA versus GER



Load GER 2008				Load CA 2005			
cf	73.53%	rrf_{pos}	1.19%	cf	54.58%	rrf_{pos}	1.05%
$cf_{Q>=0.8}$	17.99%	μ_{pos}	2.74%	$cf_{Q>=0.8}$	14.27%	μ_{pos}	2.12%
$r_{cf0.8}$	0.32	μ_{neg}	-2.12%	$r_{cf0.8}$	0.35	μ_{neg}	-2.07%
P_{min}	44.70%	$x_{y=0}$	56.40%	P_{min}	36.29%	$x_{y=0}$	50.59%

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Data basis: GER: Germany ENTSO-E, 2010 reference year 2008, CA: California CAISO, 2010, reference year 2005

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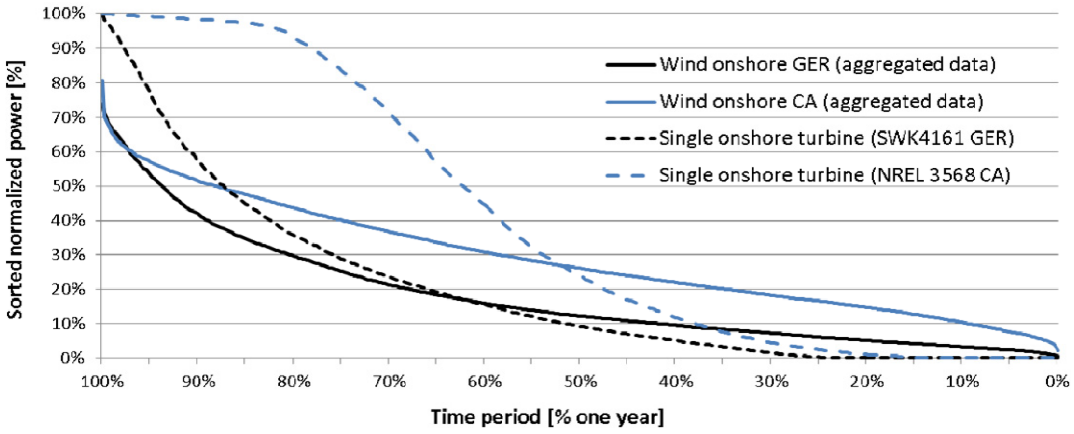
Wind generation

CA versus GER

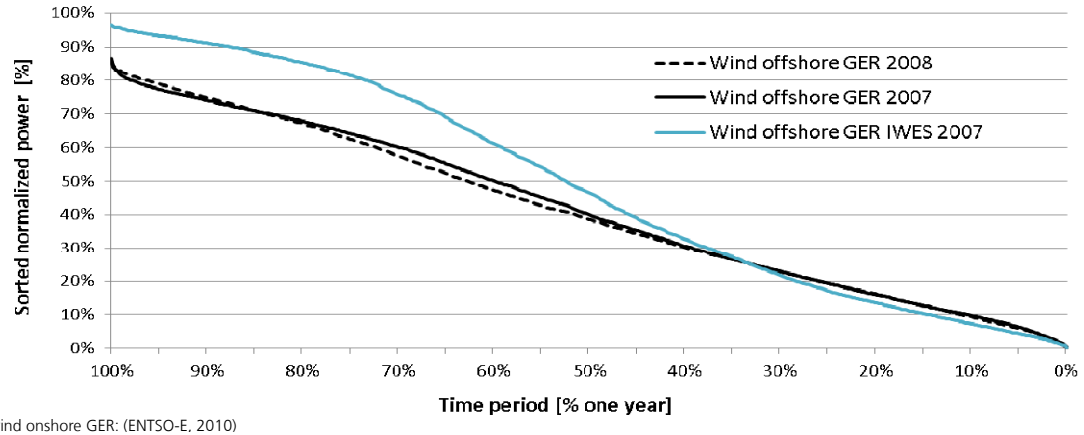
Onshore wind

	Wind onshore GER 2008	Wind onshore CA 2005
Capacity factor	19.99%	28.88%
Ramp rate factor	0.66%	1.25%
P_{min}	0.56%	2.02%
P_{max}	82.51%	80.75%

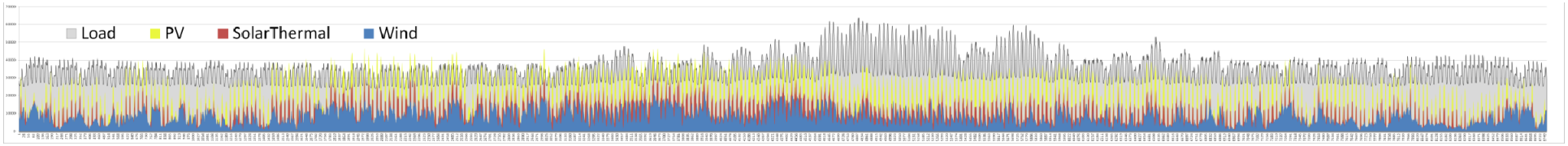


Offshore wind

	Wind offshore GER 2007	Wind offshore GER 2007 IWES
Capacity factor	41.33%	48.42%
Ramp rate factor	2.04%	0.95%
P_{min}	0.40%	0.18%
P_{max}	86.71%	96.45%



Source: SWK 4161 GER: (Stadtwerke Karlsruhe, 2011); NREL 3568: (NREL, 2009); wind onshore CA: (CASO, 2011); wind onshore GER: (ENTSO-E, 2010)



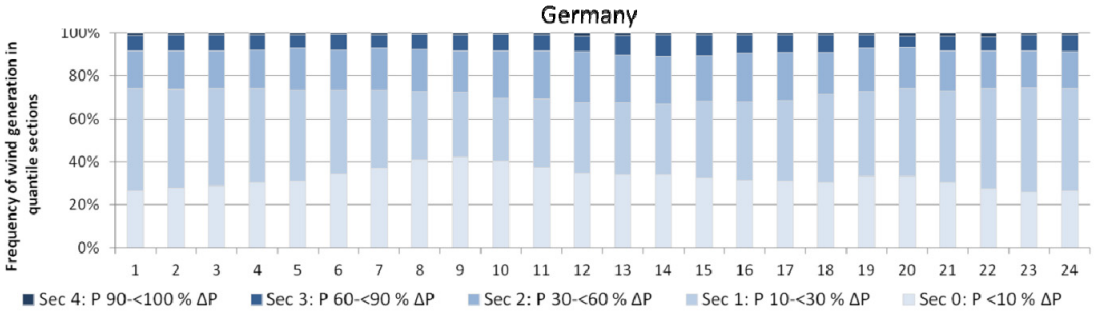
Yearly availability of wind onshore

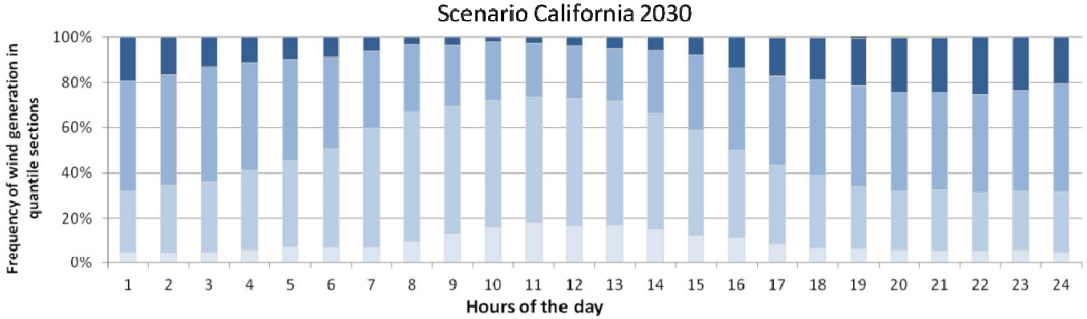
GER:

- No regular daily pattern
- Frequency of quintile P < 10% is high

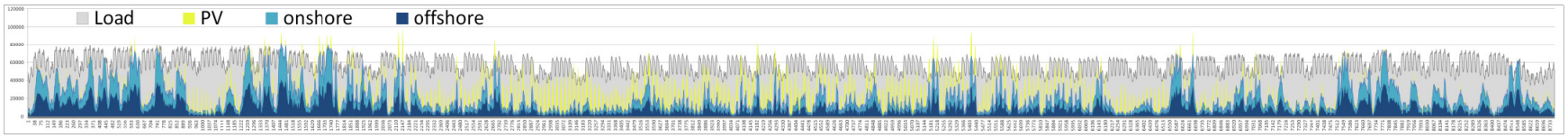
CA:

- Regular daily pattern
- Main peak generation between 17 and 24



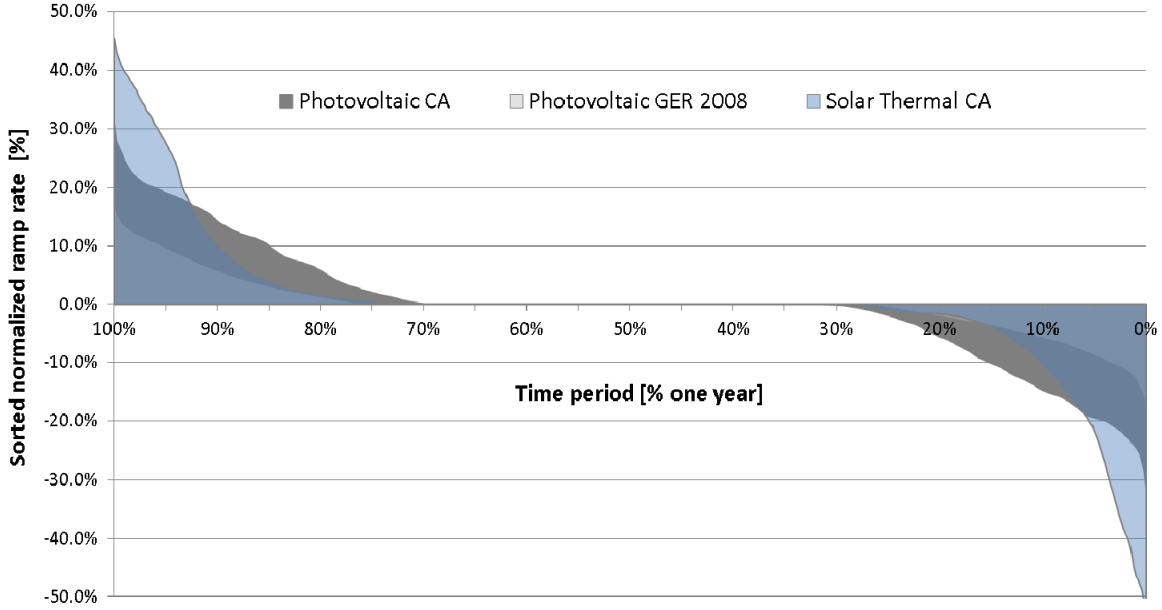


Wind onshore GER 2008					Wind onshore CA 2005				
Quantile	% of peak power	Number of events	t mean	t_σ	Quantile	% of peak power	Number of events	t mean	t_σ
Sec. 0	< 8.8	173	16.5	20.5	Sec. 0	< 9.9	122	6.6	7.2
Sec. 1	8.8 - 25.1	173	34.1	61.0	Sec. 1	9.9 - 25.6	122	64.9	127.8
Sec. 2	25.1 - 49.7	100	24.8	29.3	Sec. 2	25.6 - 49.2	267	16.7	19.3
Sec. 3	49.7 - 74.3	47	15.9	14.0	Sec. 3	49.2 - 72.9	168	6.7	6.1
Sec. 4	>74.3	**16**	**6.1**	3.8	Sec. 4	>72.9	**2**	**3.0**	0.0



Photovoltaic generation

CA versus GER



Photovoltaics GER 2008				Photovoltaics CA 2005				Solar Thermal CA 2005			
cf	10.02%	rrf_{pos}	**1.35%**	cf	24.66%	rrf_{pos}	**3.18%**	cf	25.81%	rrf_{pos}	**3.20%**
$cf_{Q>=0.8}$	7.57%	μ_{pos}	4.36%	$cf_{Q>=0.8}$	15.45%	μ_{pos}	7.60%	$cf_{Q>=0.8}$	16.88%	μ_{pos}	10.79%
$r_{cf0.8}$	3.10	μ_{neg}	-4.71%	$r_{cf0.8}$	1.68	μ_{neg}	-10.40%	$r_{cf0.8}$	1.89	μ_{neg}	-9.37%
P_{min}	0.00%	$x_{y1=0}$	72.76%	P_{min}	0.00%	$x_{y1=0}$	69.76%	P_{min}	0.00%	$x_{y1=0}$	70.36%
P_{max}	64.62%	$x_{y2=0}$	29.47%	P_{max}	98.42%	$x_{y2=0}$	30.61%	P_{max}	95.72%	$x_{y2=0}$	34.14%

Data basis: GER: Germany ENTSO-E, 2010 reference year 2008, CA: California CAISO, 2010, reference year 2005

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Mobile battery storage

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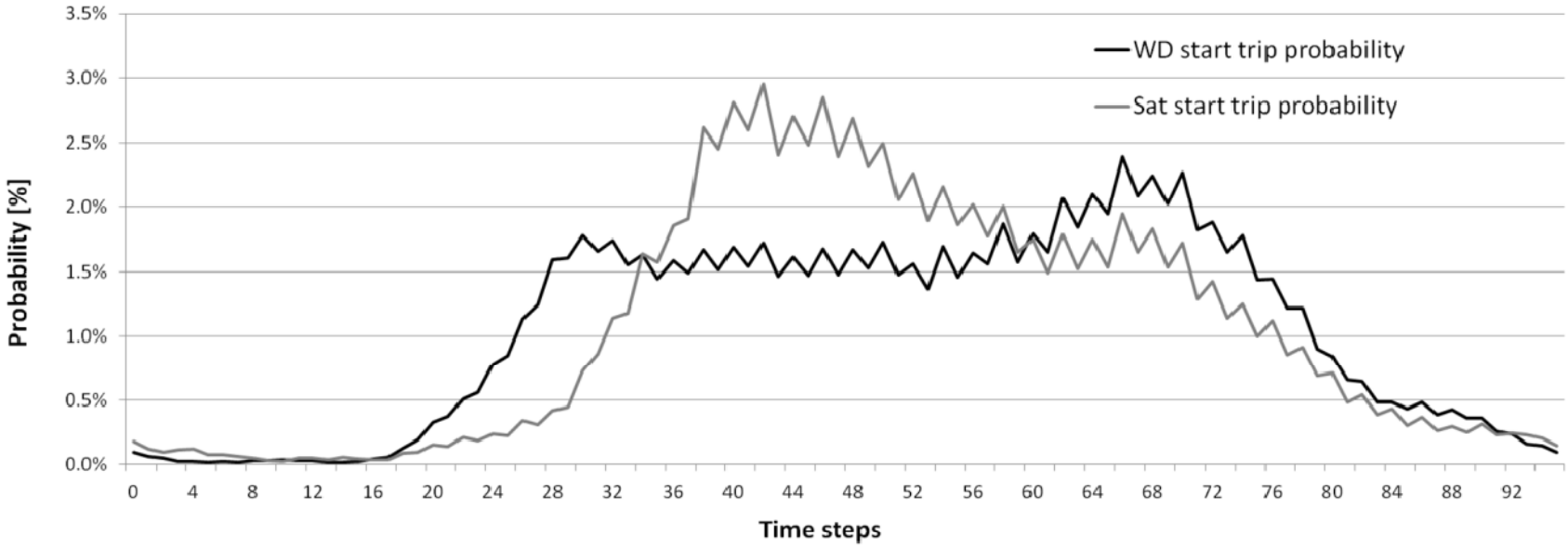
Mobility behavior

Characteristics of mobile storage

- Trip start times, driving distances and driving time determine the energy available for demand response.
- Mobility behavior varies on different days of the week.
- Vehicle users show specific driving characteristic.
- German users with positive TCO drive more than 15,000 km per year and live in urban areas.



Data basis: MID, 2010

TCO: Total costs of owner ship

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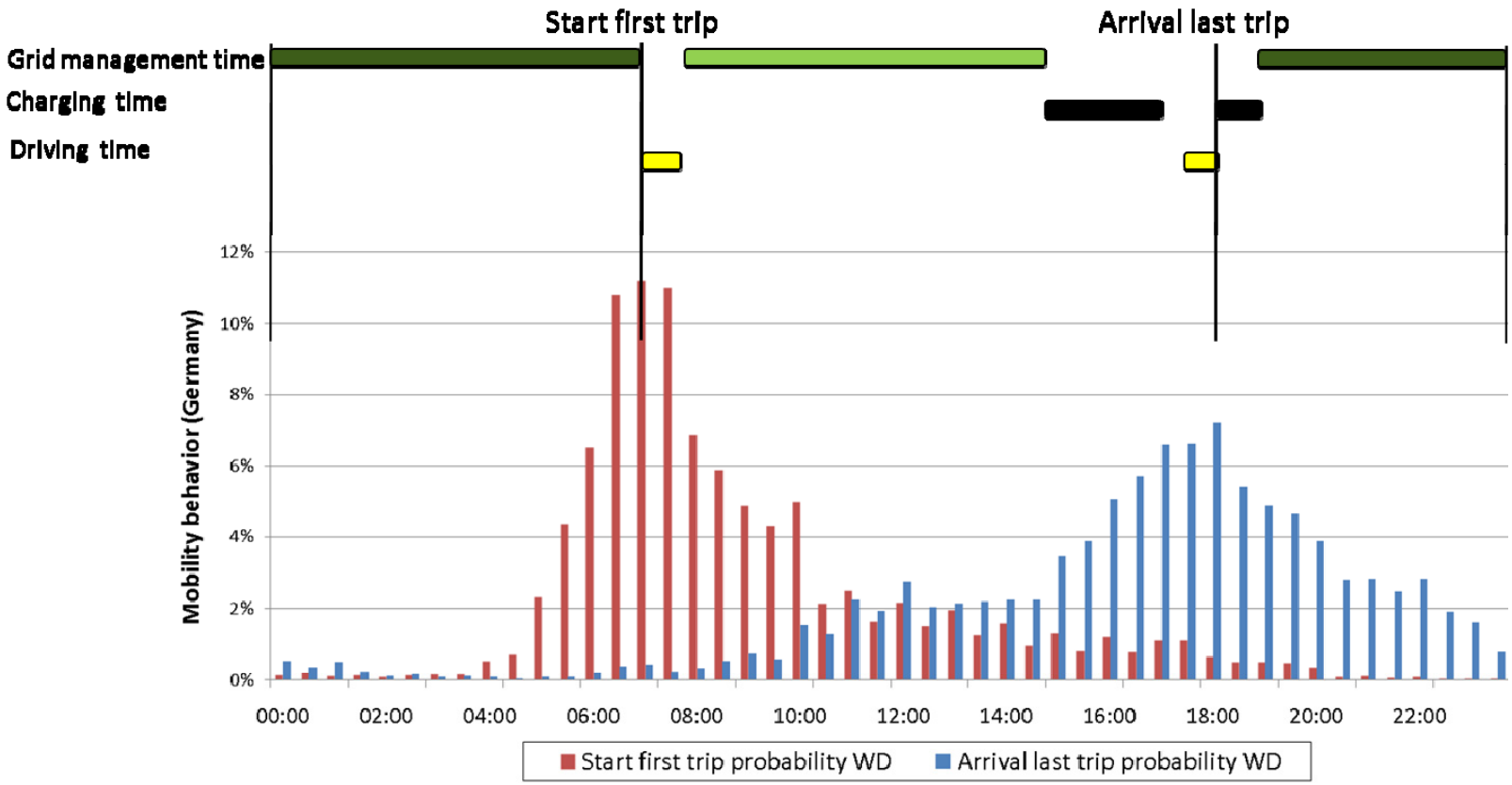
Grid management time

Characteristics of mobile storage



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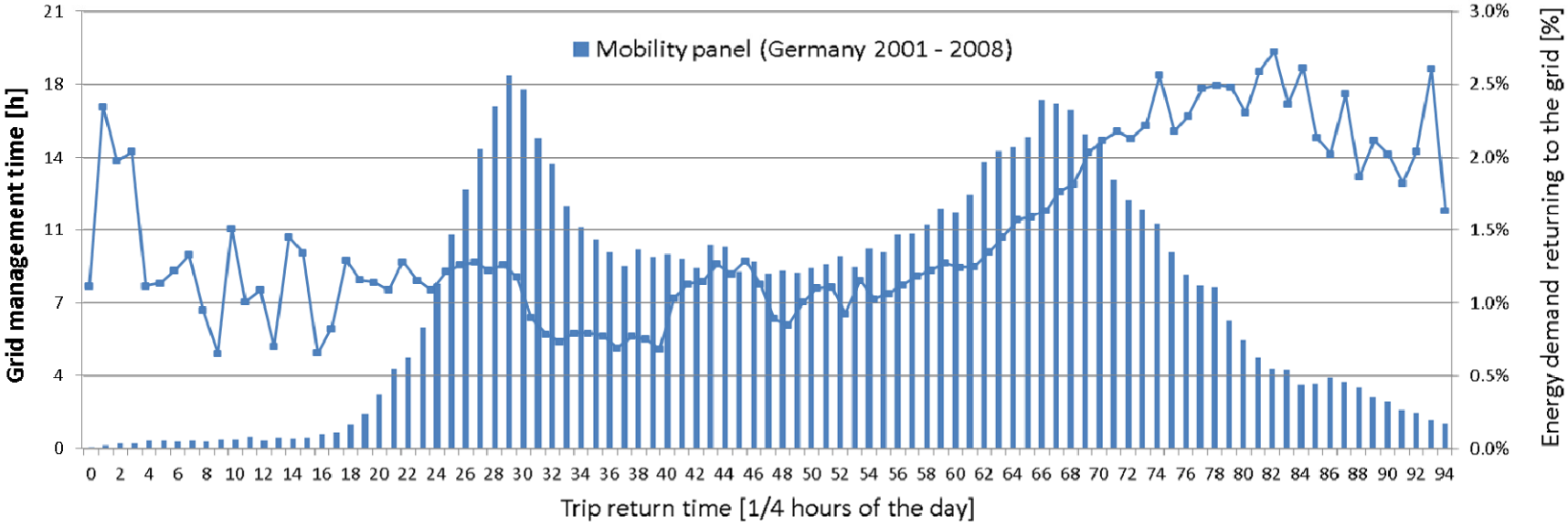
Grid management time

Characteristics of mobile storage



Data basis: MOP, 2001 - 2008

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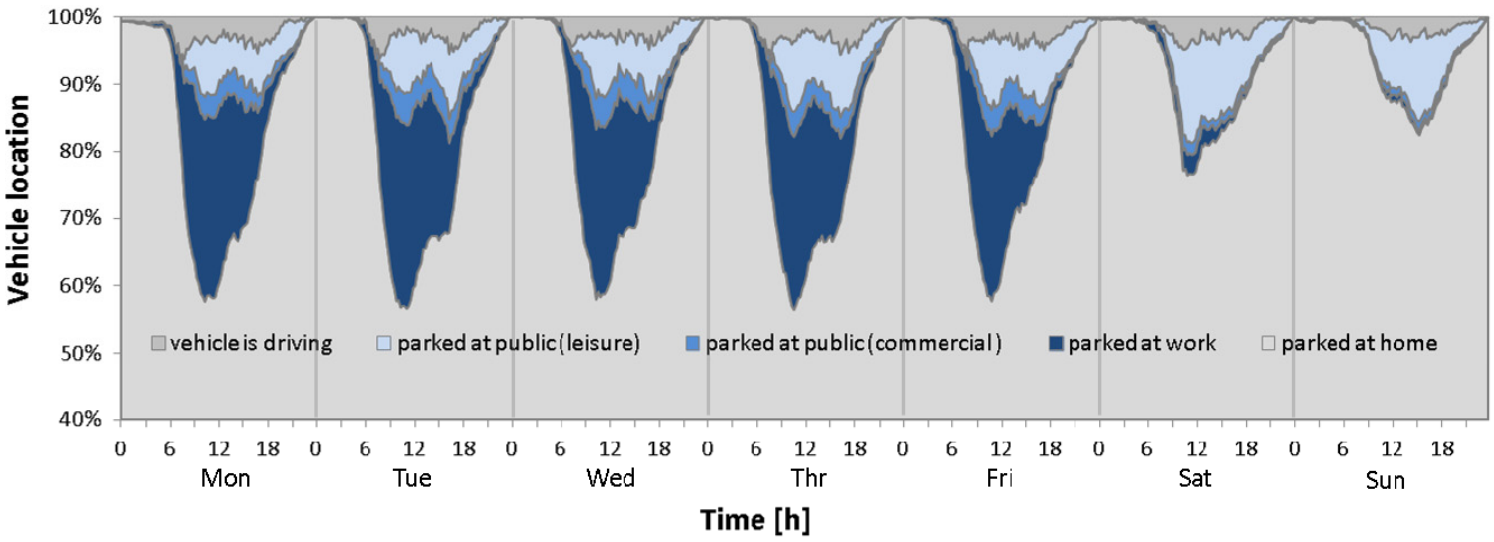
Vehicle locations

- Vehicles mainly park at home.
- Grid management time while parking at home is the longest.
- Public parking is diverse, difficult to predict and does only slightly increase the electric driving share
- Beside a smart meter in the vehicle, private homes are most attractive to install smart infrastructure.



Data basis: MOP, 2001 - 2008

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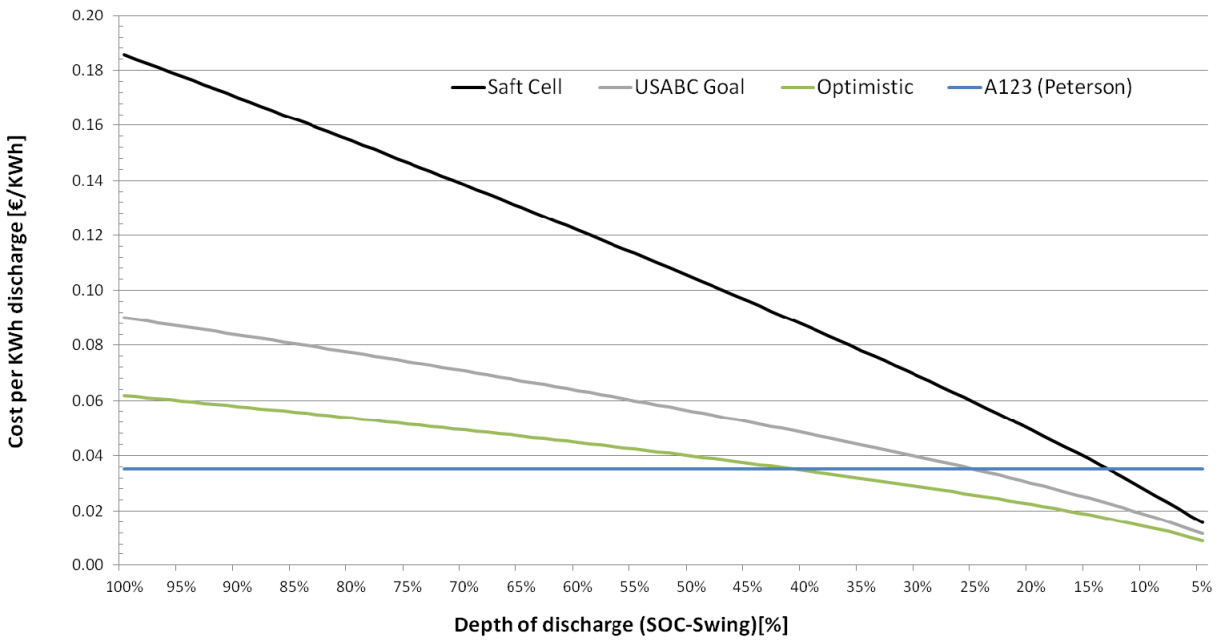
Optimistic V2G cost assumptions



Discharge costs: $c_{dis}(x_0, x_{DOD}) = \frac{c_{bat}}{C_{life}}$

Costs for one kWh proceeded: $c_{dis}(x_0, x_{DOD}) = \frac{c_{bat}}{C_{life}(DOD) * x_{DOD} * e_{bat}}$

- V2G with today's Li- Ion batteries is in most cases not economic
- The average base peak price spread was 3ct./kWh in Germany 2010
- Advanced batteries with higher cycle life and lower investment could be competitive in electricity markets with a high base-peak- spread of the electricity prices (6 ct./kWh)
- Aging can be implemented based on the depth of discharge or the energy throughput

Investment c_{bat} =247 €/kWh$_{usable\ energy}$ for the battery system

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Simulation Method

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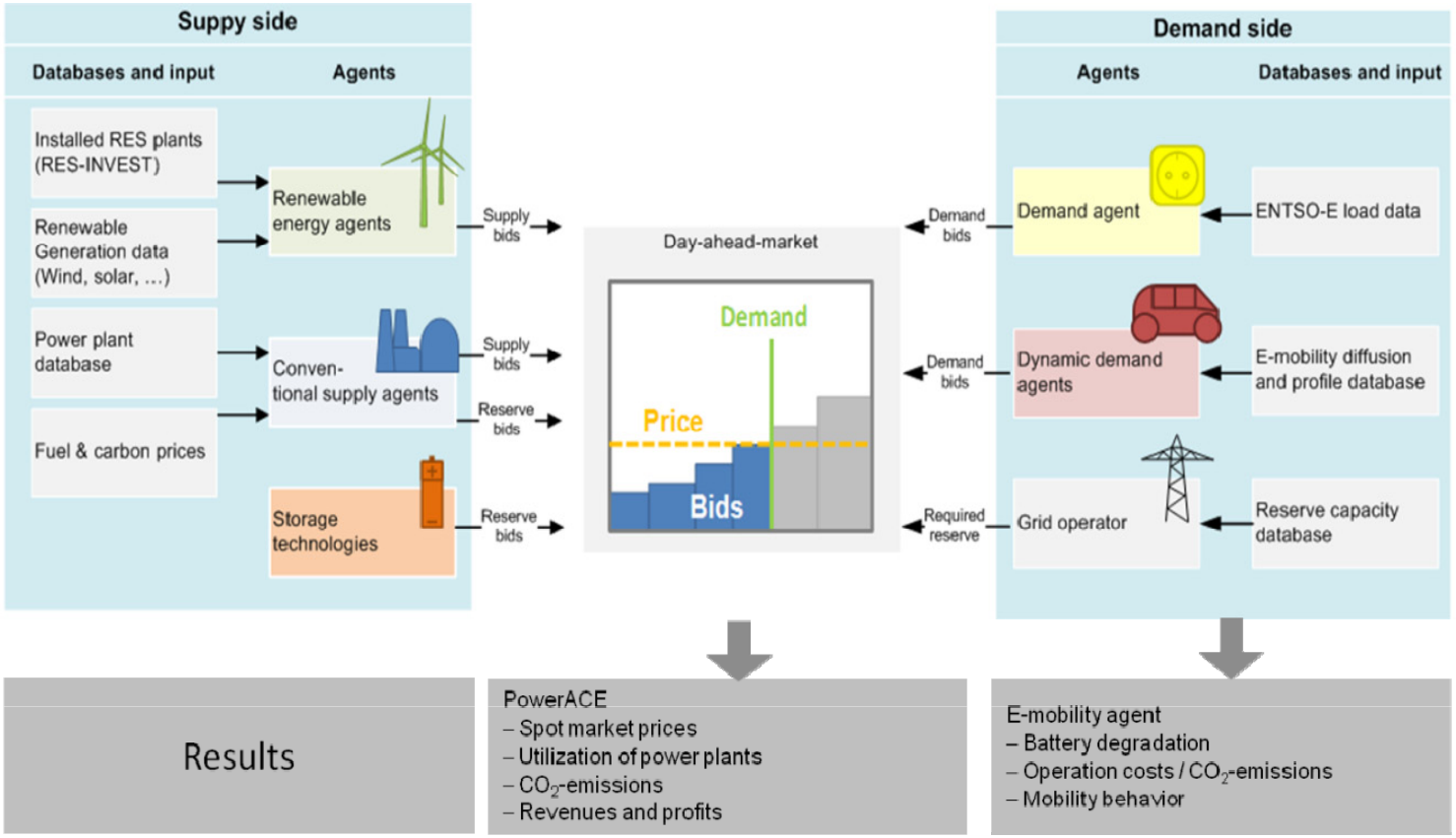
PowerACE Model



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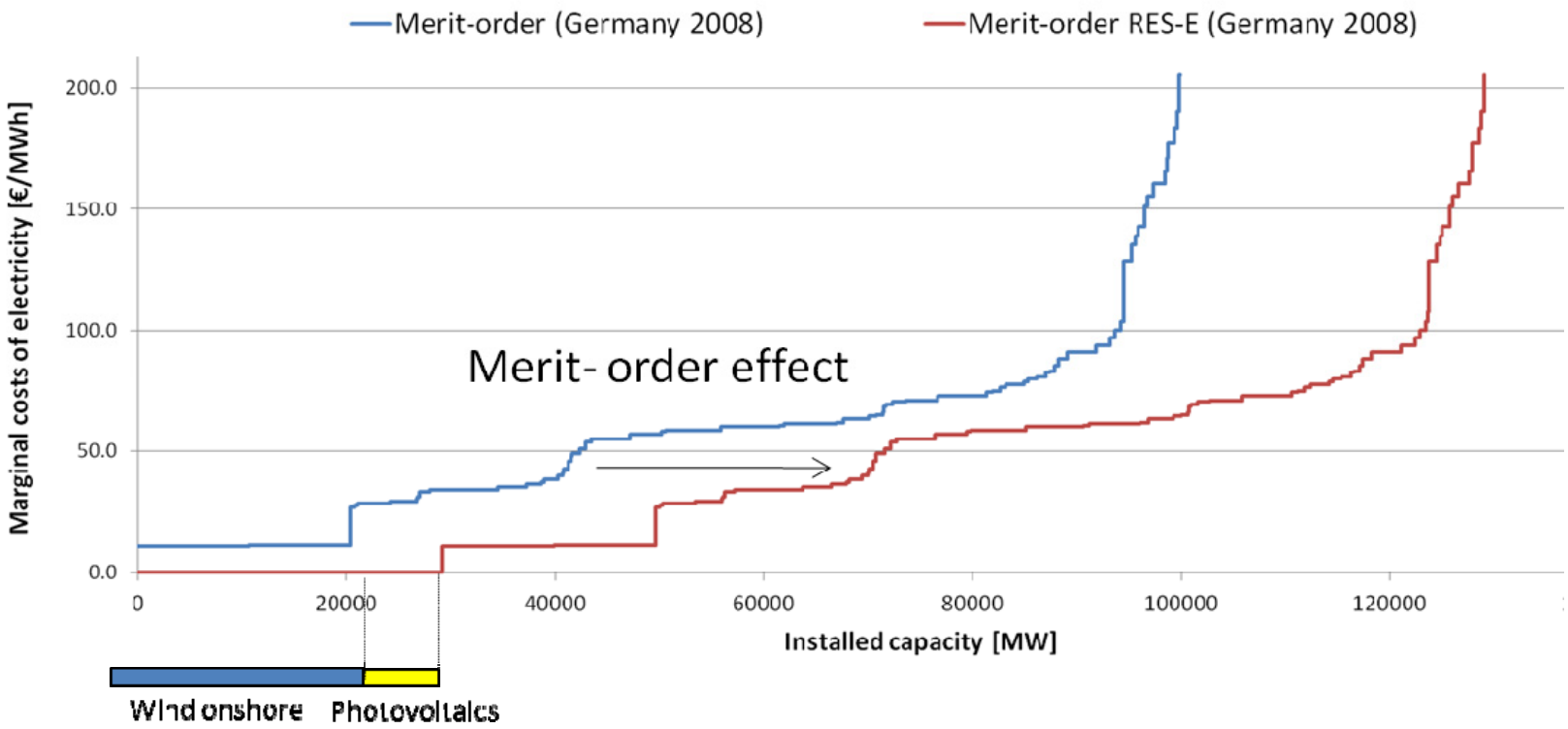
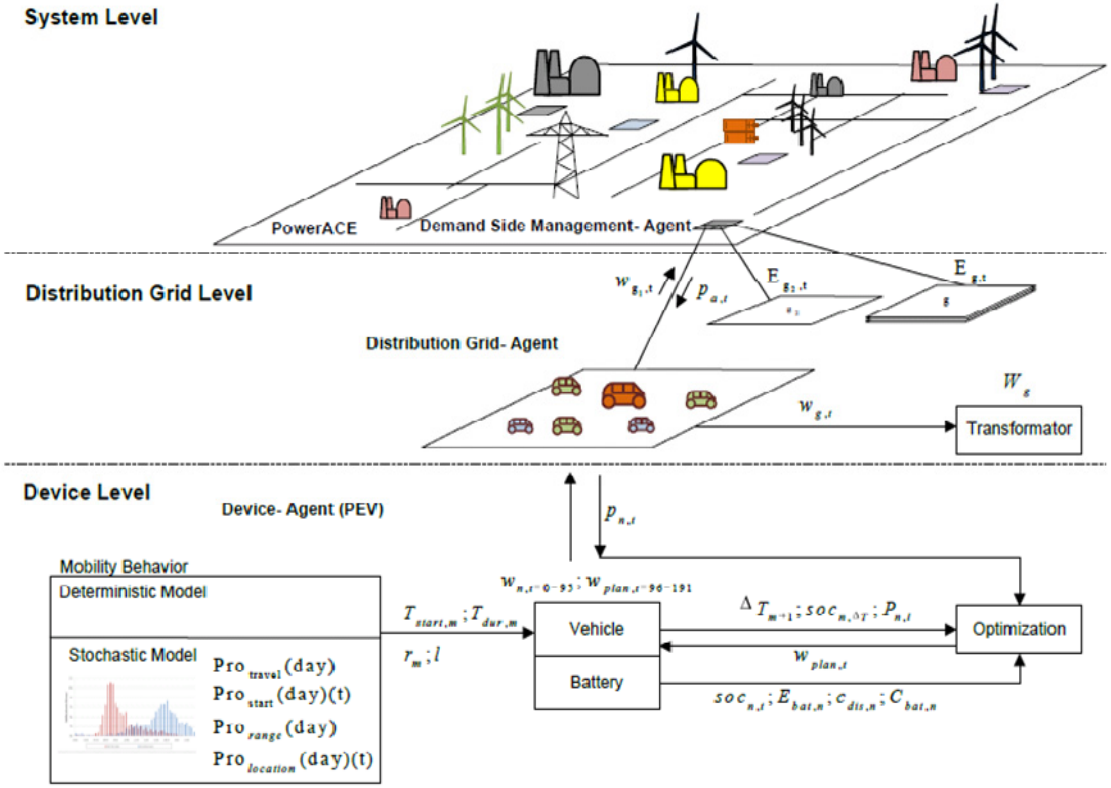
Merit-order effect



Marginal costs: $c_{marginal} = \frac{1}{\eta} * p_{fuel} + \frac{1}{\eta} * q_{co_2} * p_{CO_2}$

p_{fuel}	Fuel price	[€/MWh]
p_{co2}	Price for CO_2	[€/t]
q_{co2}	CO_2 coefficient	[g CO_2/kWh]
η	Efficiency	

Price-based demand response and V2G



- Prices on system level account for the merit-order effect
- To avoid simultaneous action of automated demand response a variable grid fee is added to the price signal on system level
- To account for 12 million vehicles 12,000 vehicles are modeled using individual driving behavior
- Critical review:
  - The model does not account for transmission grid restrictions
  - System exchange is not considered
  - Consumer acceptance for dynamic prices and price sensitivity are not considered
  - Perfect tip forecasting

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Scenario

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Vehicle Scenario

Plug-in vehicle type:

Device	Type (km)	Usable storage [kWh]	Grid connection power [kW]	Equivalent energy use [kWh_{el}/km] **	CA 2030 (6.7 million PEVs)	GER 2030 (12 million PEVs)
1	PHEV (25)	4.5	4	0.18	31.60%	31.60%
2	PHEV (57)	12	4	0.21	50.40%	50.40%
3	BEV (100)	15	8	0.15	13.90%	13.90%
4	BEV (167)	30	8	0.18	4.00%	4.00%

Penetration scenario:

	CA 2030			GER 2030		
Type	**Vehicles [thousand]**	**Connection power [GW]**	**Storage capacity [GWh]**	**Vehicles [thousand]**	**Connection power [GW]**	**Storage capacity [GWh]**
PHEV (25)	2,150	8.60	9.68	3,885	15.54	17.48
PHEV (57)	3,430	13.72	41.16	6,585	26.34	79.02
BEV (100)	945	7.56	14.18	1,230	9.84	18.45
BEV (167)	275	2.20	8.25	300	2.40	9.00
Sum	**6,800**	**32.08**	**73.26**	**12,000**	**54.12**	**123.95**

- PHEVs' TCO is lower compared to BEVs with battery swapping or high power charging
- Usable battery storage is expected to be <15 kWh
- For CA and GER, the same proportionate share of PEVs is assumed
- Grid connection is between 4 kW and 8 kW
- The power/energy ratio of the total fleet for CA 2030 and GER 2030 is 0.441/h.
- German pumped storage plants provide 7.76 GW with a rated volume of 224.31 GWh (ratio: 0.035 1/h).

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Energy scenario

Details of CAISO scenario

Technology	Installed capacity [MW]
Total photovoltaics (PV)	**6,661**
Large PV	3,527
Distribute PV	1,045
Customer Side PV	1,749
Out of State PV	340
Total solar thermal (ST)	**4,458**
Large Solar Thermal	4,058
Out of State ST	400
Wind	**9,436**

- CA solar time series are combined from different installation types
- The energy production of fluctuating RES is 47.6 % for CA and GER in the 2030 scenario
- In the CA 2030 scenario solar generation accounts for 24 % of total generation vs. 11% for GER 2030
- The installed capacity of fluctuating RES is 162 % and 96.7 % of the peak load for GER and CA, respectively.

Fluctuating renewable energy sources (RES)

Scenario		Wind onshore	Wind offshore	Photo-voltaics	Solar thermal	Share of fluctuating RES-E (peak load; generation)	Total electricity demand (peak load; generation)	Unit
GER 2030	Capacity	37.8	25	63	-	162.00%	77.8	GW
	Generation	87	95	57		47.60%	502.1	TWh
CA 2030	Capacity	28.2	-	19.9	13.3	96.70%	63.5	GW
	Generation	71.403	-	43.051	30.158	47.60%	303.806	TWh

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Results

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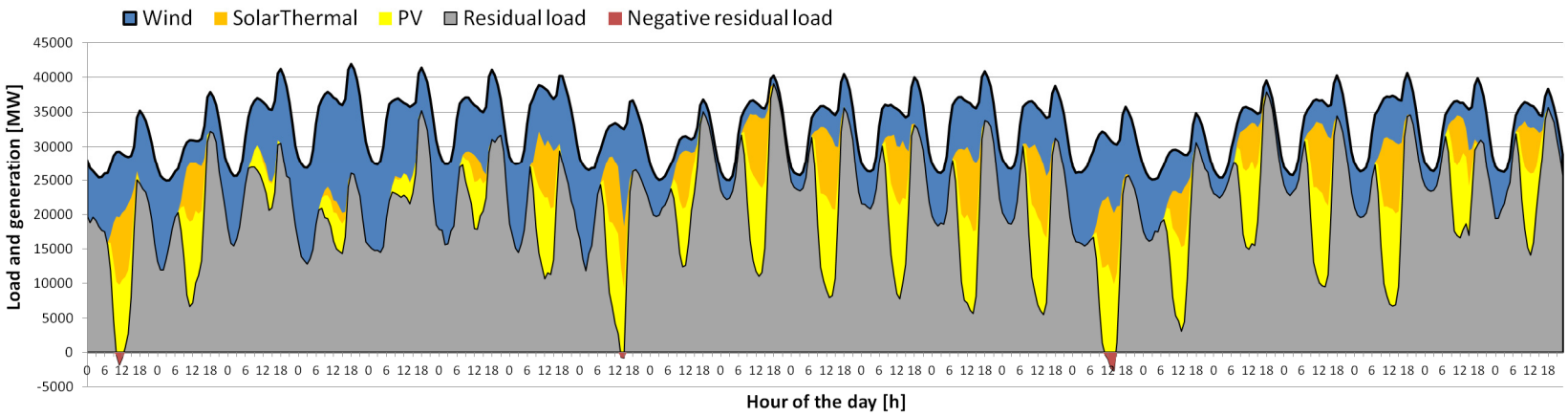
A new thinking of base and peak load is necessary



- For the scenario CA 2030 the electricity system is dominated by solar generation
- Low residual load periods are likely during noon
- Peak residual load often occurs during the evening and morning hours
- But still periods with low solar and wind generation or several days with strong winds can occur
- Periods when fluctuating generation exceed the electricity demand (negative residual load) most likely occur between 12:00 and 16:00 in the CA 2030 scenario

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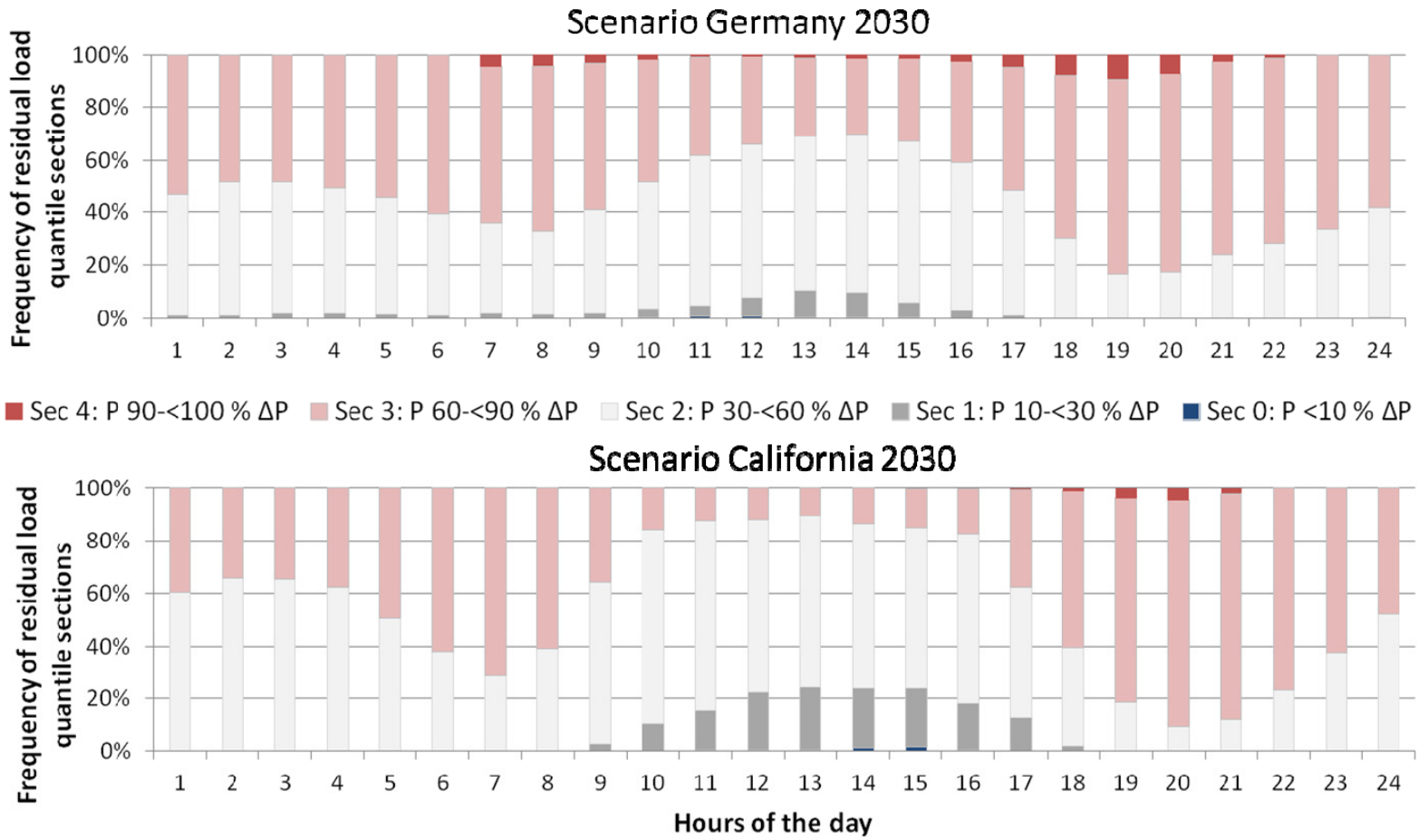
Scenario 2030: Yearly availability of the residual load



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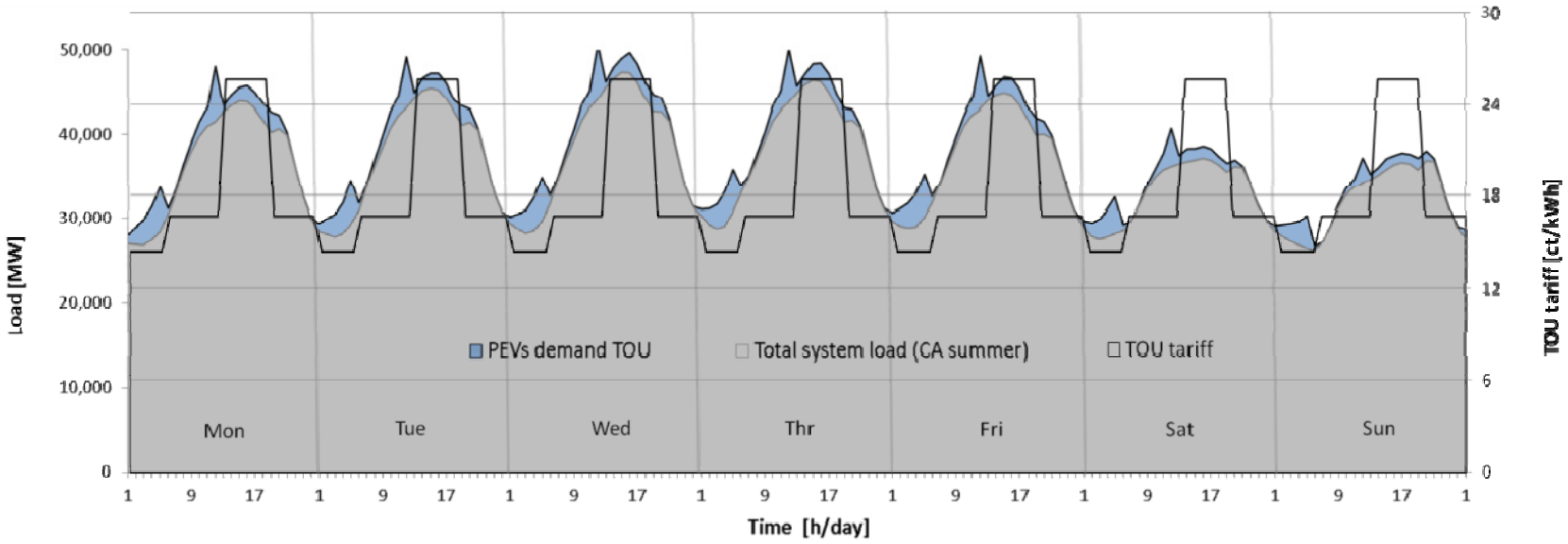
Time of use rate and automated demand response of plug-in electric vehicles



Time of use rate for electric vehicles:

	Super Off Peak	Off Peak	Peak	Off Peak
Time period	Midnight – 5 am	5 am – 12 pm	12 pm – 6 pm	6 pm - Midnight
Rate	14.4ct/kWh	16.7ct/kWh	25.7ct/kWh	16.7ct/kWh

Source: TOU rate (Pacific Gas and Electric, 2011)

- For automated demand response time of use rates (TOU) can increase ramping and load peaks
- For the grid integration of fluctuating RES common TOU rates are too inflexible

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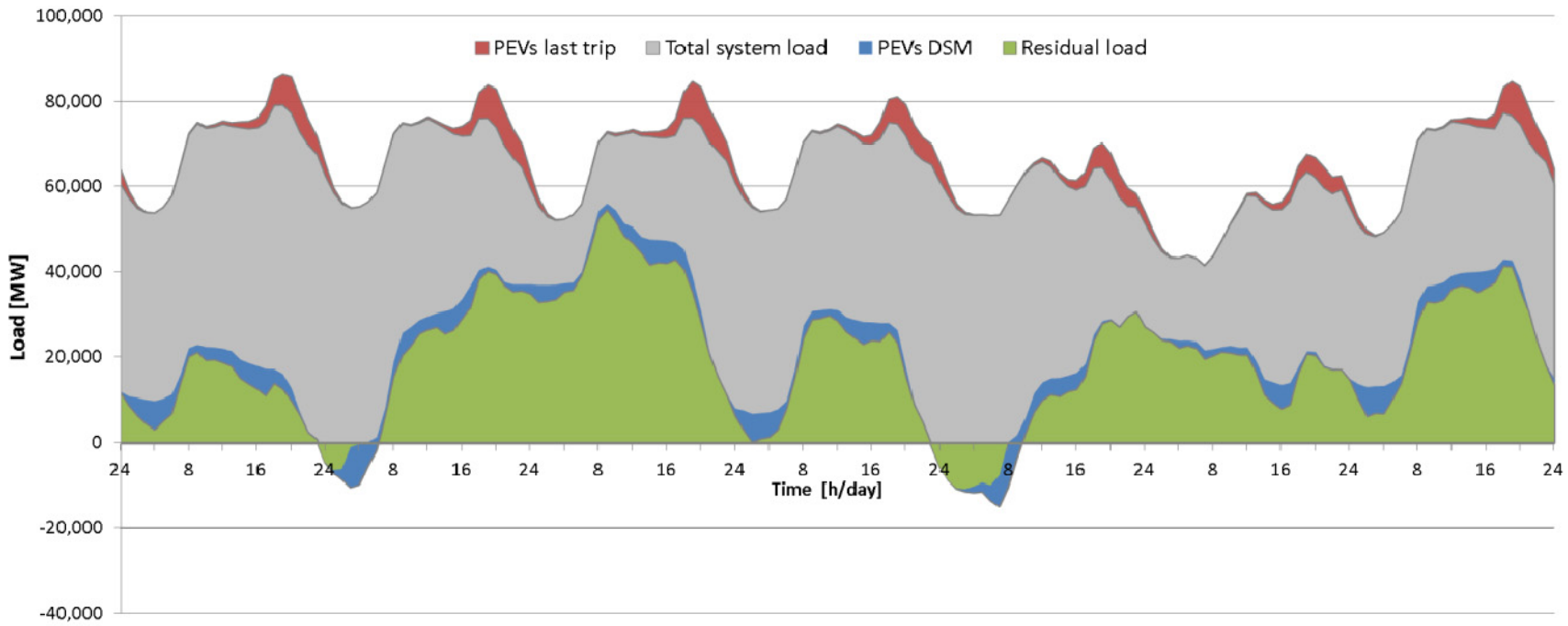
Scenario GER 2030: Demand side management (DSM) using real-time prices



- Last trip charging increases the peak load and does not allow to balance fluctuating generation
- The implemented demand side management mechanism follows the residual load without curtailment of driving behavior

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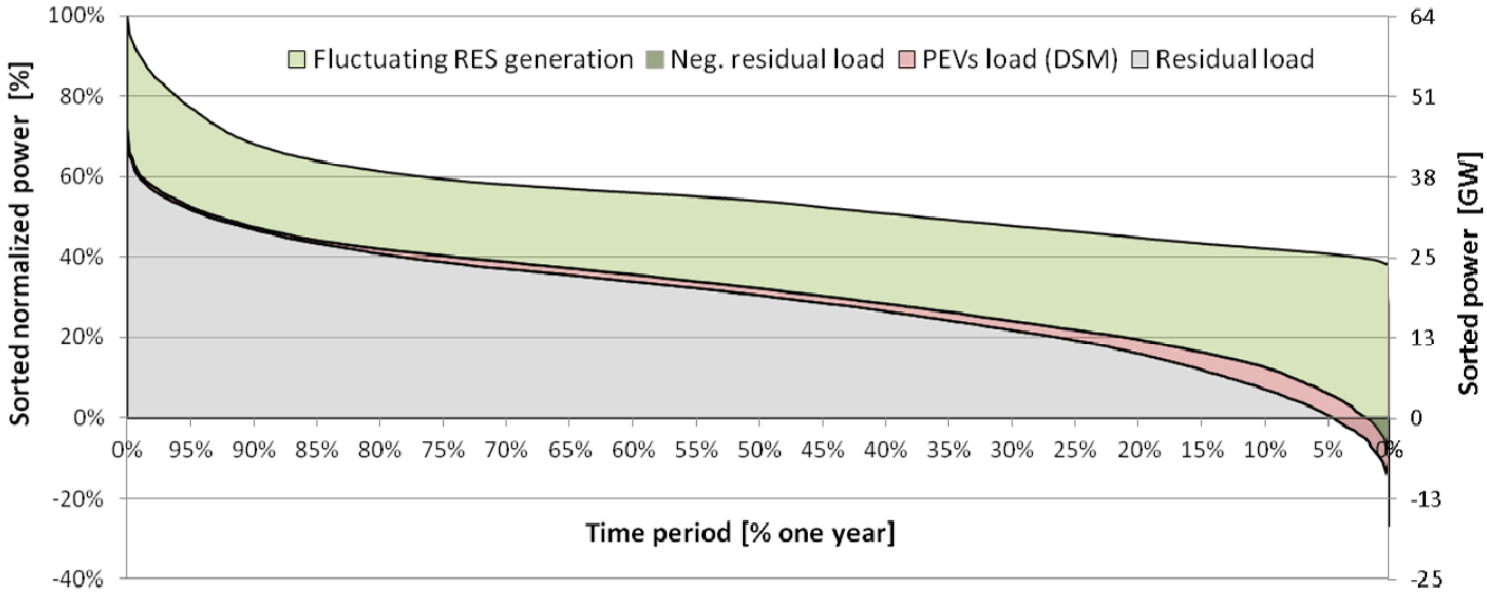
CA scenario 2030: Plug-in electric vehicles (PEVs) automated demand response



	E,pos	E,neg	P,min	P,max
	TWh		GW	
Load	303.8		23.1	63.5
Residual load	159.2	-1.53	-16.8	45.6
PEVs load (DSM)	14.0	-0.45	-10.9	45.9

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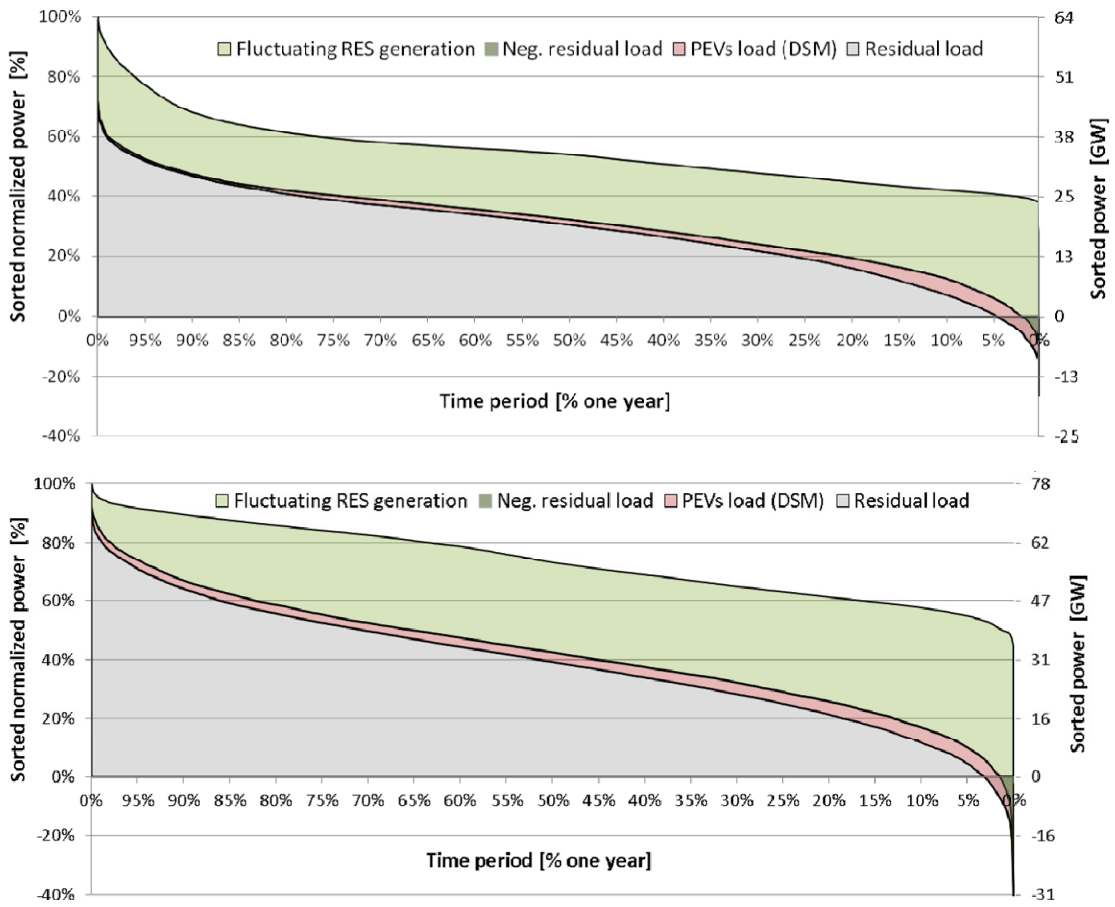
Scenario 2030: CA versus GER



- In CA high capacity credit of RES: peak residual load is 71.1 % vs. 90.4 %
- The need for peak capacity in CA is reduced whereas the needed peak capacity in GER is rising
- Negative residual load consumed by PEVs in CA is higher: 73 % vs. 64 %
- Reduction of negative residual load peak for CA and GER is in the same range

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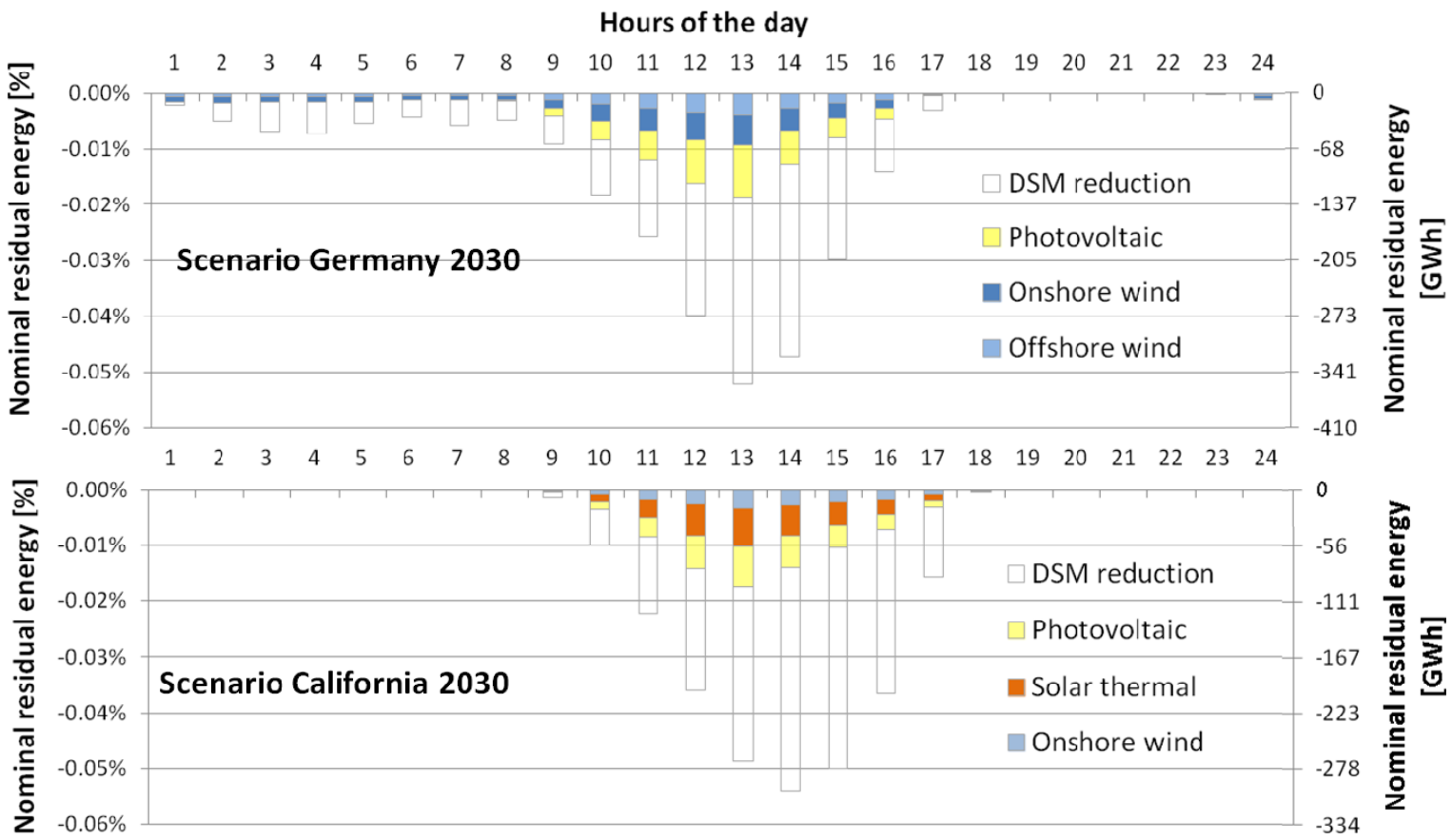
Hour of the day with negative residual load and reduction due to PEVs' DSM



DSM: Demand side management

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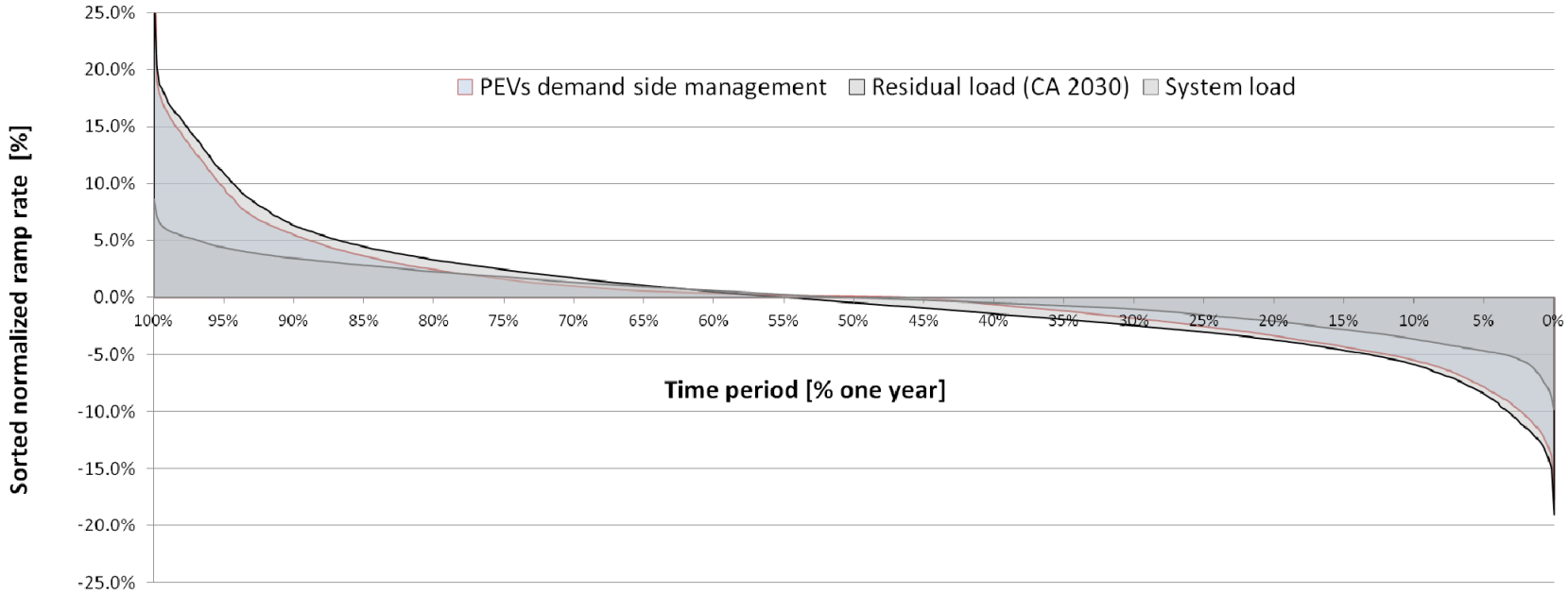
Scenario CA 2030: Reduction of ramp rates



	rrf_{pos}	μ_{pos}	σ_{pos}	μ_{neg}	σ_{neg}	$x_{y=0}$
System load	1.05%	2.12%	1.60%	-2.07%	1.83%	50.59%
Residual load (CA 2030)	1.99%	4.38%	4.53%	-3.63%	3.14%	54.70%
PEVs demand side management	1.68%	3.07%	4.10%	-3.64%	3.06%	45.76%

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Conclusion

- The electricity generation from fluctuating renewable energy sources (RES) determines the residual load of low carbon electricity systems.
- The **contribution of storage and demand response** therefore is very **sensitive** to generation **time series** and **weather years**.
- Plug-in electric vehicles can be characterized as **short term storage** with very **high power to energy ratio** (Factor 10 compared to hydro pump storage) and restrictions due to **mobility behavior**
- The **daily pattern of RES** power generation in the CA 2030 scenario **favors the integration of electricity** from fluctuating generation compared to the GER 2030 scenario
- The same argument applies, if photovoltaics and wind power are compared with each other. The daily pattern of **photovoltaic** generation **favors** the **storage capabilities of electric vehicles**, if charging infrastructure is available where the vehicles are parked during the day.

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Thank you for your attention !

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First German offshore wind turbine (http://www.alpha-ventus.de/)

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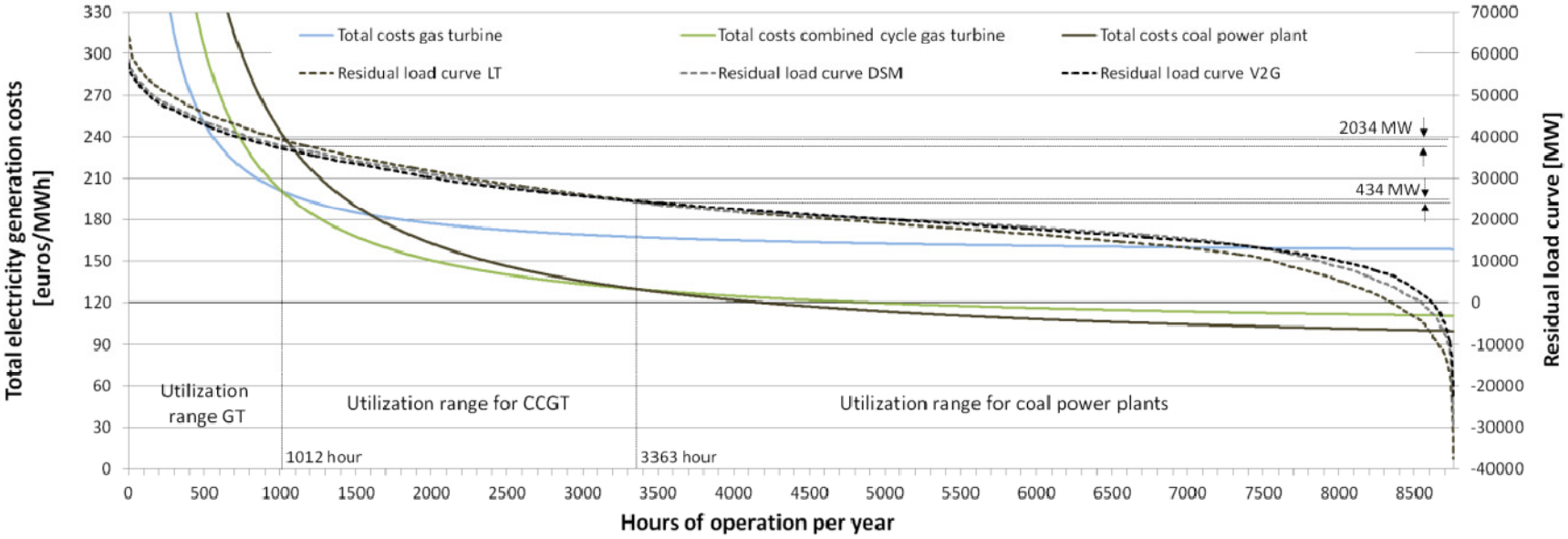
Optimal power plant park



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Time series used

Time series	Scenario	Method of data preparation	Weather year	Source
Wind onshore GER	GER 2030	Measured	2007/2008 / 2009	EEX, 2011
Wind offshore GER		Measured		Schubert, 2010/11
Wind offshore IWES GER		Weather data (model)	2007	Lange, 2011
Photovoltaics GER		Weather data (measured)	2007/2008 / 2009	Schubert, 2011
Load GER		Measured		ENTSO-E, 2011
Wind CA	CA 2030	Weather data (measured and model data)	2005	CAISO, 2011 and NREL, 2009
Solar Thermal CA				
Photovoltaics CA				
Load CA		Measured	2005	

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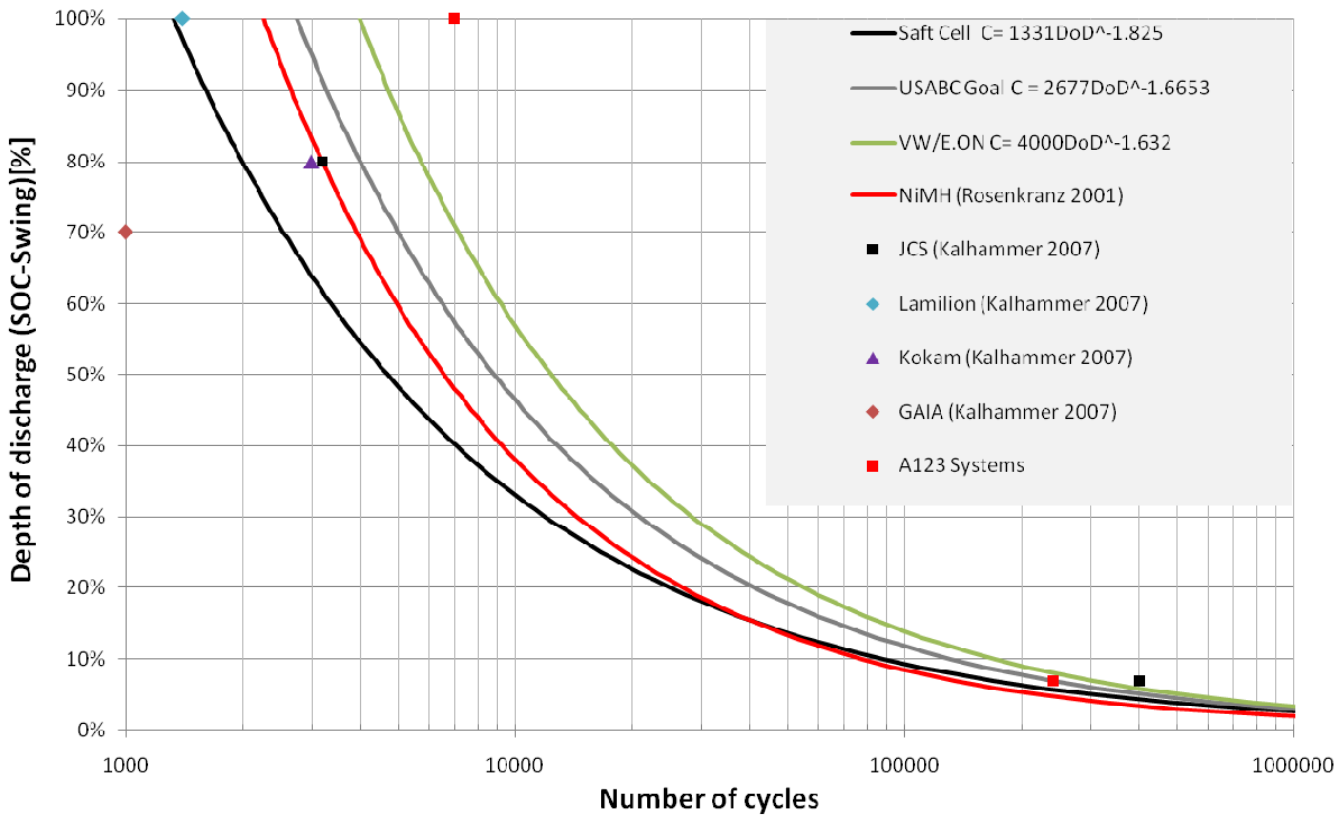
Cycle life time in dependence on depth of discharge



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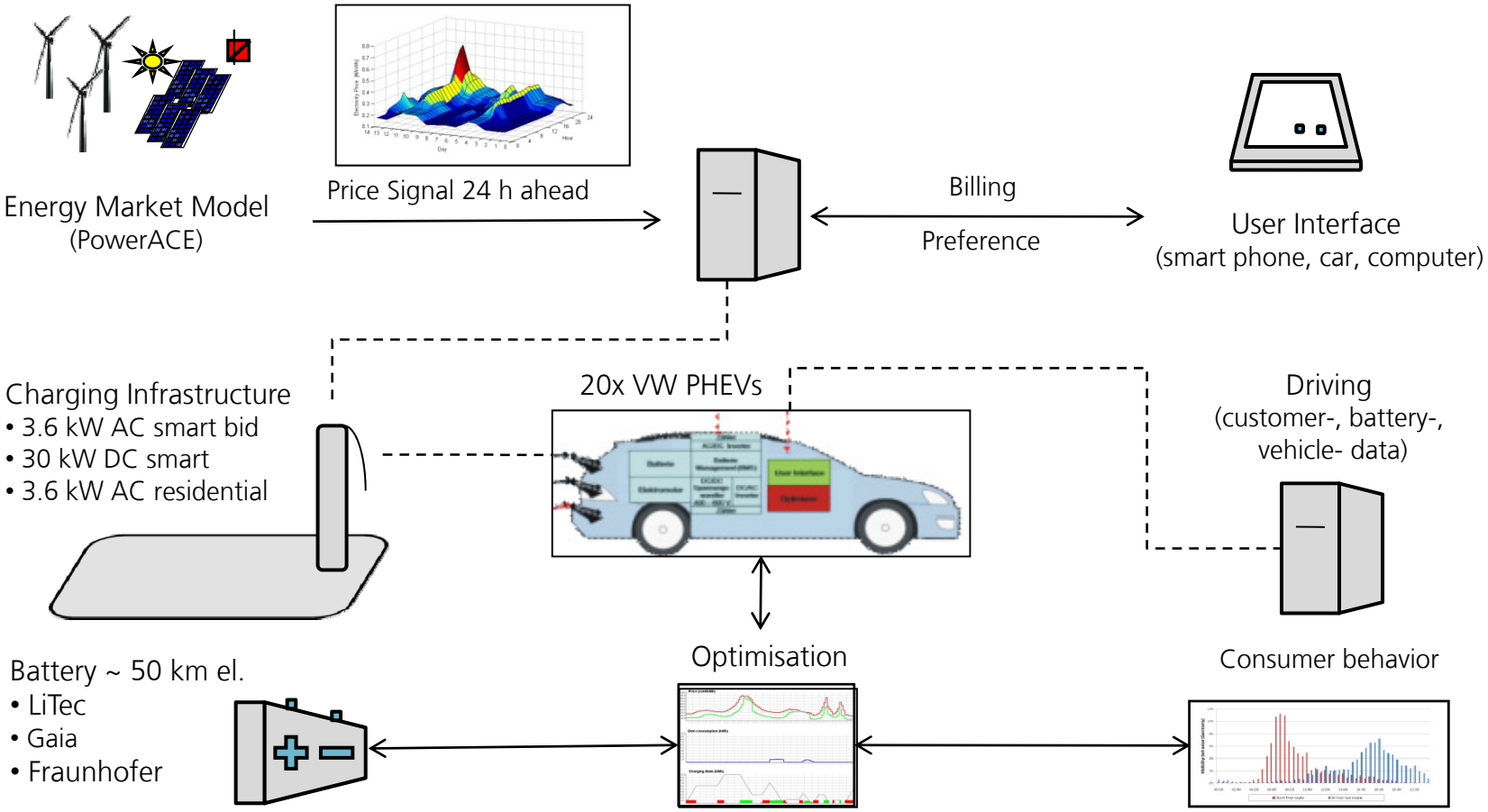
Interaction of different players in the E.ON and Volkswagen fleet test



- **Focus:** System Integration of Renewable Energies, Batteries and PHEVs
- **Funding:** German Federal Ministry for the Environment
- **Partners:** VW, E.ON, IFEU, Evonik, Fraunhofer, DLR, University Münster
- **Duration:** 4 years until 2012

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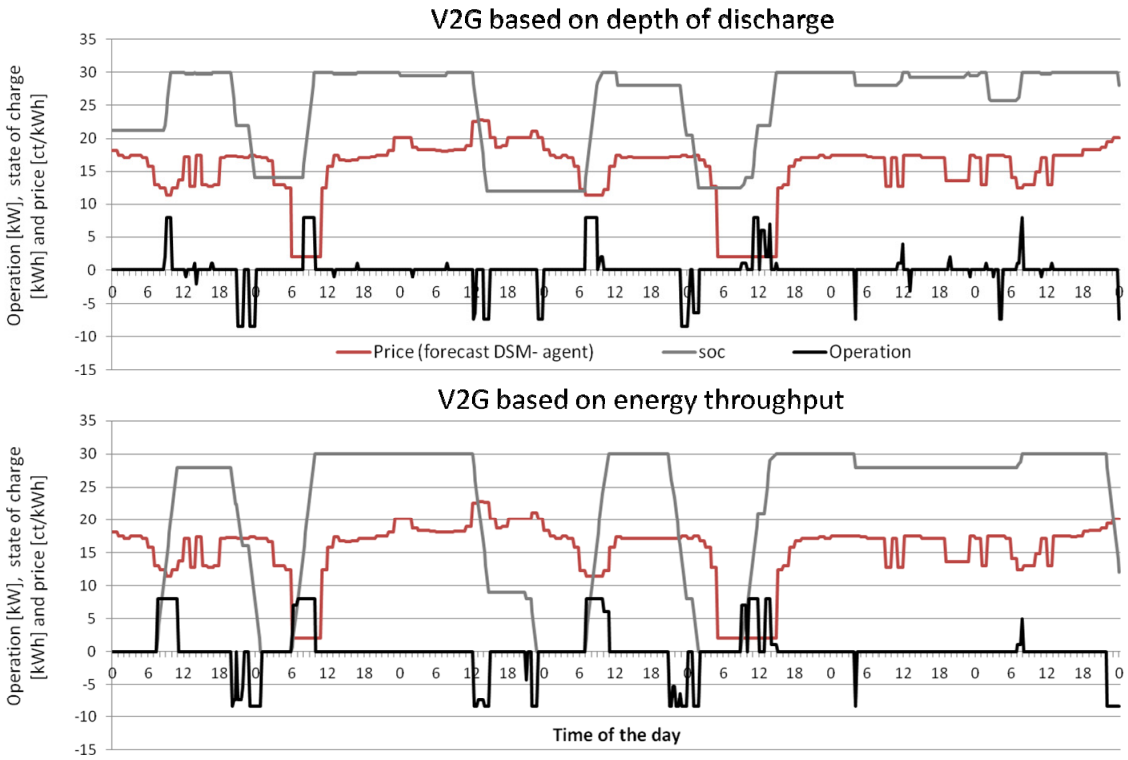
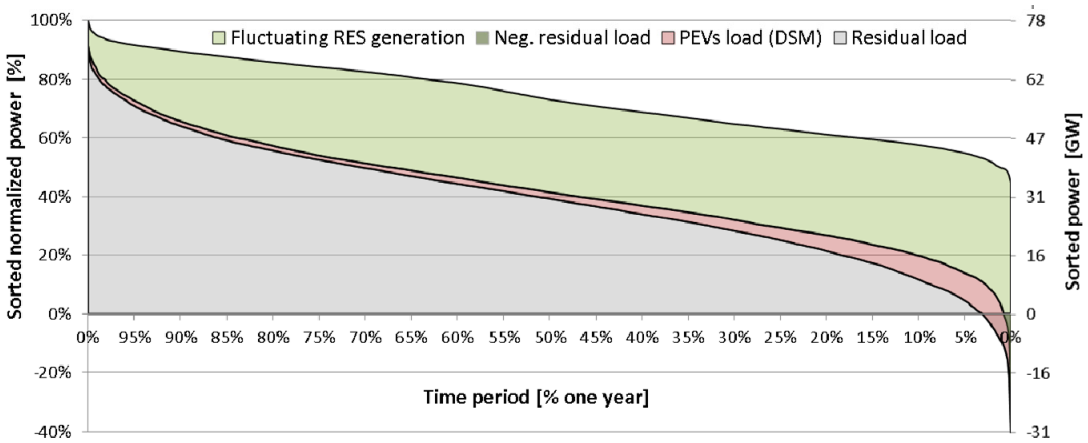
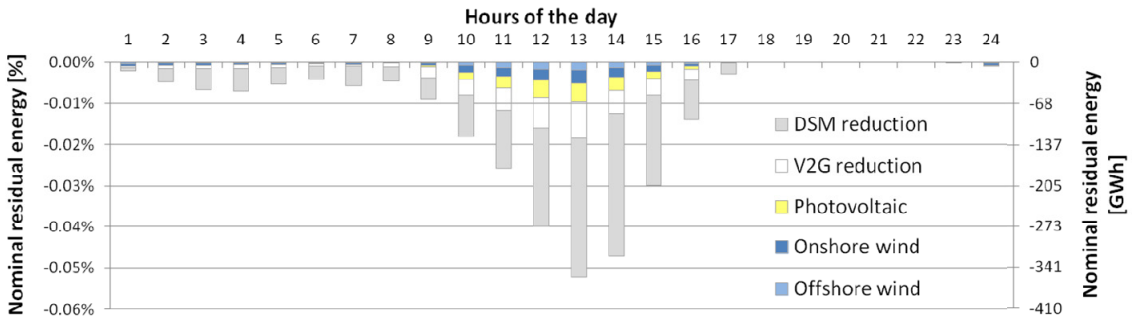
V2G depth of discharge vs. energy throughput



Scenario GER 2030: Possible contribution of V2G





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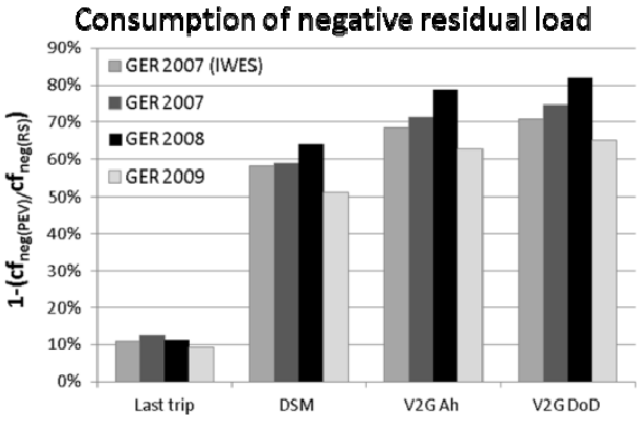
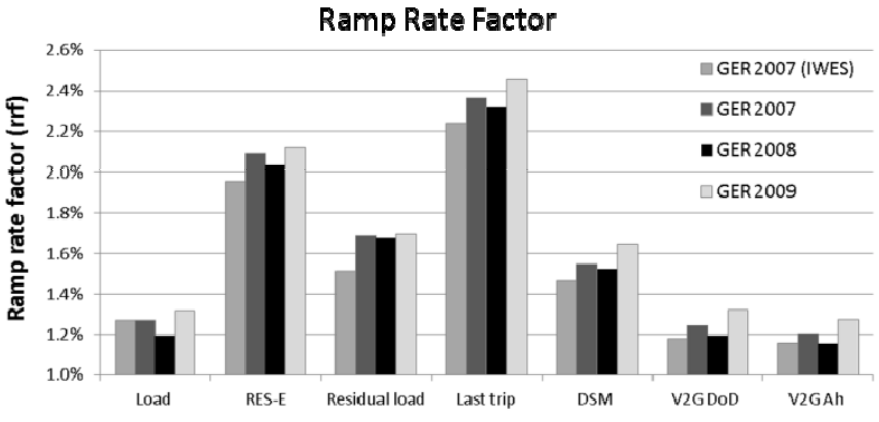
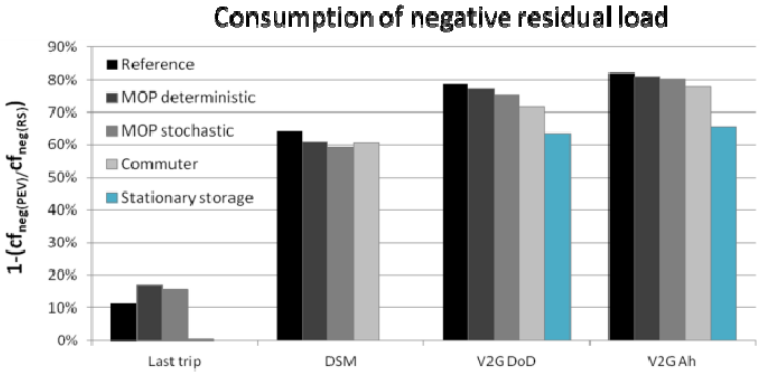
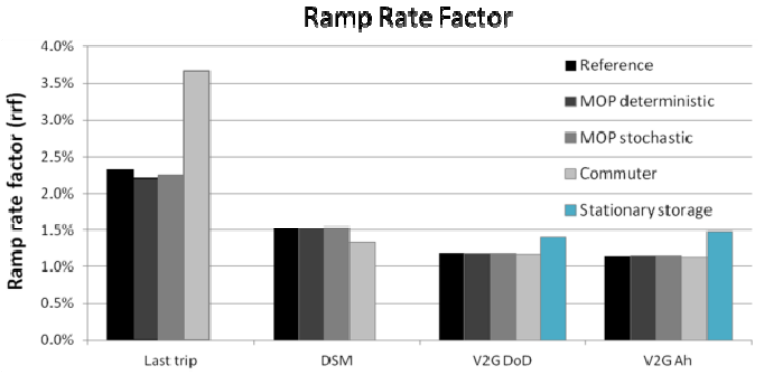
Sensitivity: Weather year and mobility data









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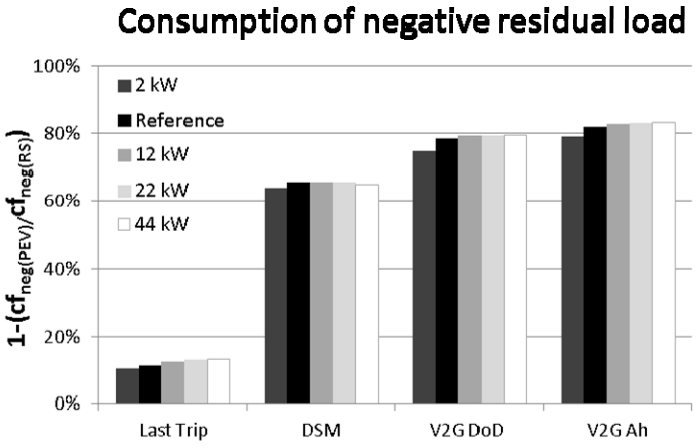
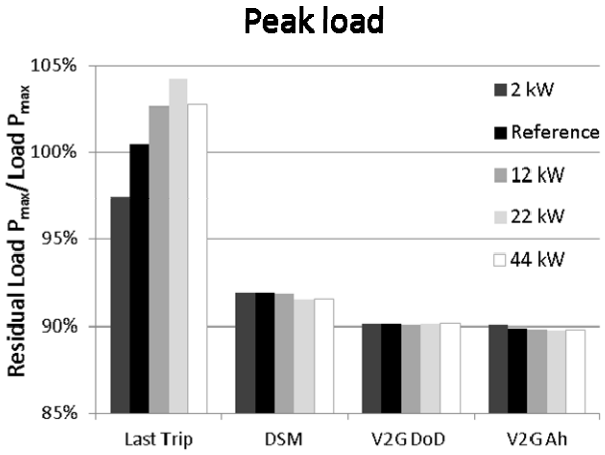
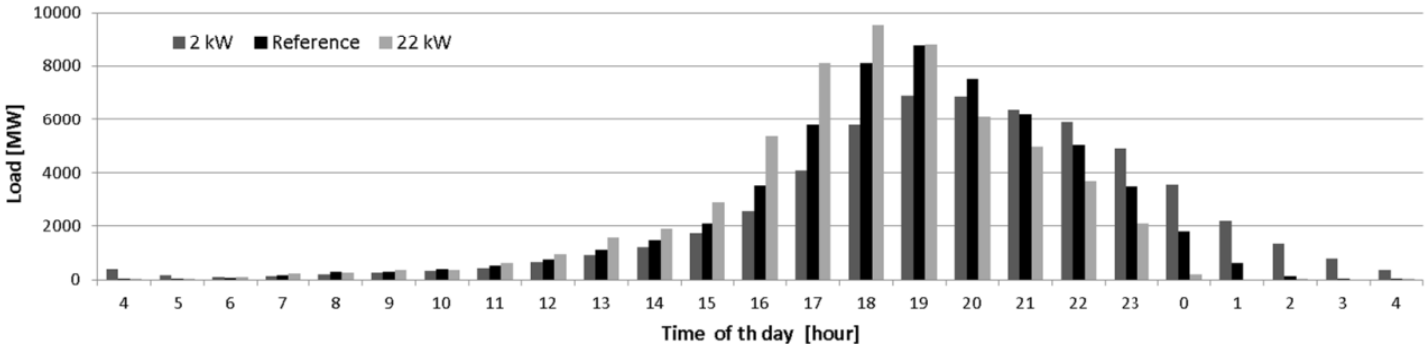
Sensitivity: Power







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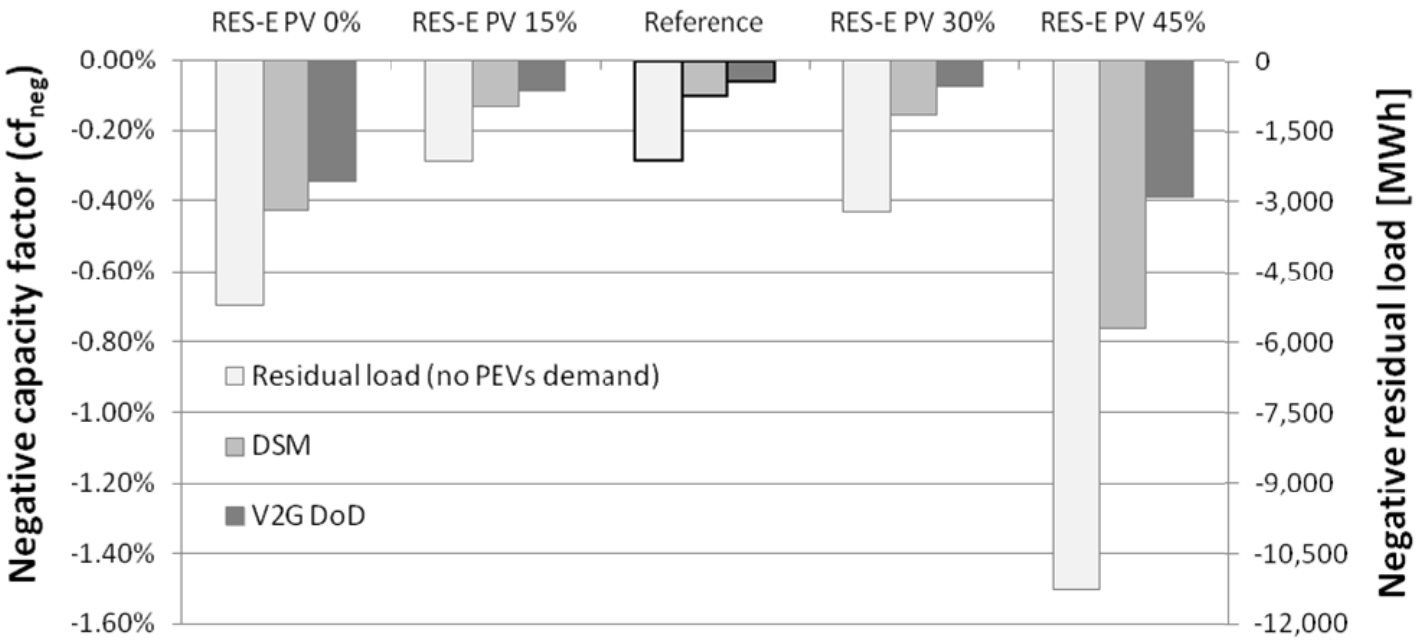
Negative residual load change varying the generation share of photovoltaics



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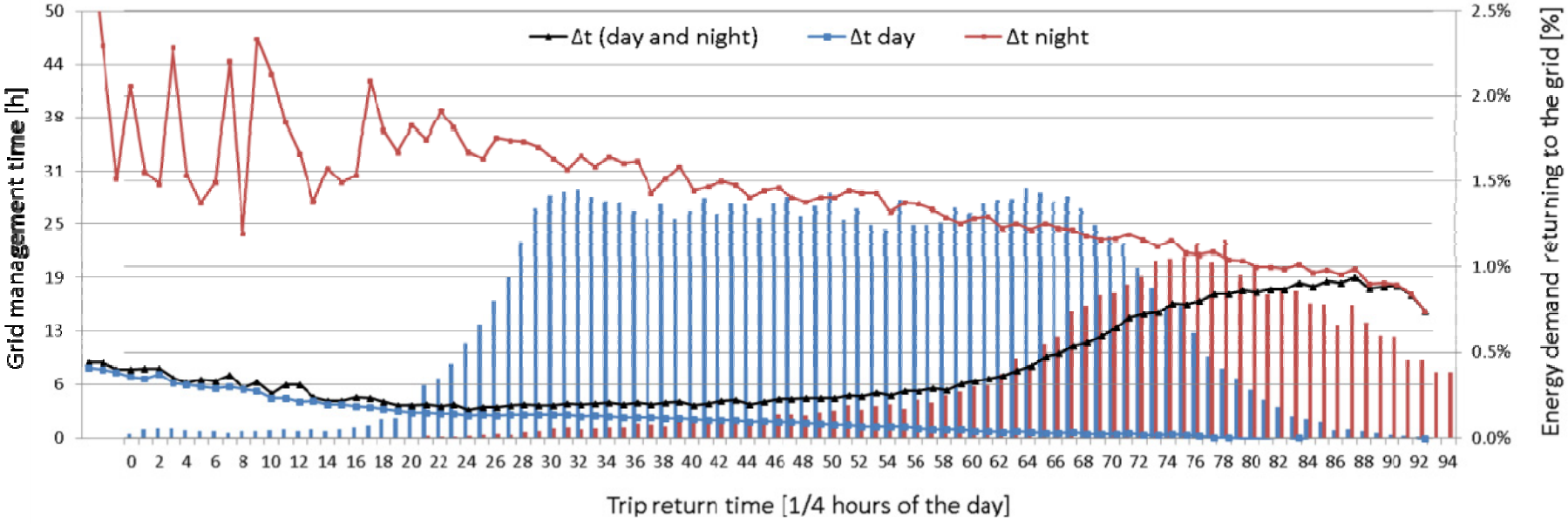
Grid management time during the day and after the last trip



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Scenario 2030 parameters

RS GER 2030				RS CA 2030			
cf_{pos}	38.8 %	rrf_{pos}	2.03 %	cf_{pos}	28.9 %	rrf_{pos}	1.99 %
cf_{neg}	-0.285 %	μ_{pos}	4.39 %	cf_{neg}	-0.278 %	μ_{pos}	4.38 %
$cf_{y=0}$	3.2 %	μ_{neg}	-3.76 %	$cf_{y=0}$	4.4 %	μ_{neg}	-3.63 %
$r_{cf0.8}$	0.51	$x_{y=0}$	53.88 %	$r_{cf0.8}$	0.50	$x_{y=0}$	54.70 %
P_{min}	-43.52 %	$Cor_{RES\text{-}load}$	34.22 %	P_{min}	-26.46 %	$Cor_{RES\text{-}load}$	46.81 %
P_{max}	90.36 %			P_{max}	71.69 %		

RS + PEVs DSM charging GER 2030				RS + PEVs DSM charging CA 2030			
cf_{pos}	42.3%	rrf_{pos}	1.52%	cf_{pos}	31.2%	rrf_{pos}	1.70%
cf_{neg}	-0.102%	μ_{pos}	2.88%	cf_{neg}	-0.076%	μ_{pos}	3.43%
$cf_{y=0}$	1.40%	μ_{neg}	-3.20%	$cf_{y=0}$	1.60%	μ_{neg}	-3.33%
$r_{cf0.8}$	0.48	$x_{y=0}$	47.35%	$r_{cf0.8}$	0.46	$x_{y=0}$	50.71%
P_{min}	-34.02%	$Cor_{RES\text{-}load+PEV}$	44.50%	P_{min}	-18.52%	$Cor_{RES\text{-}load+PEV}$	56.56%
P_{max}	91.93%			P_{max}	72.09%		

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