Karlsruhe Institute of Technology

Virtual Storages as Theoretically Motivated Demand Response Models for Enhanced Smart Grid Operations

Energy, Science and Technology 2015, Karlsruhe

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INSTITUTE FOR APPLIED COMPUTER SCIENCE (IAI)

1. Motivation and Introduction

Challenges of the future electricity system:

- increased share of renewable energies
- balance of demand and supply at all times

Approaches:

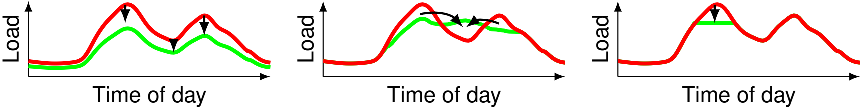
- expansion of power distribution grid, smart grid
- integration of electricity storage systems
- usage of demand side flexibility by
  - control signals → Demand Side Management (DSM)
  - price-based signals → **Demand Response (DR)**

1. Motivation and Introduction

Key success factors:

1. **data-based** Demand Response analysis

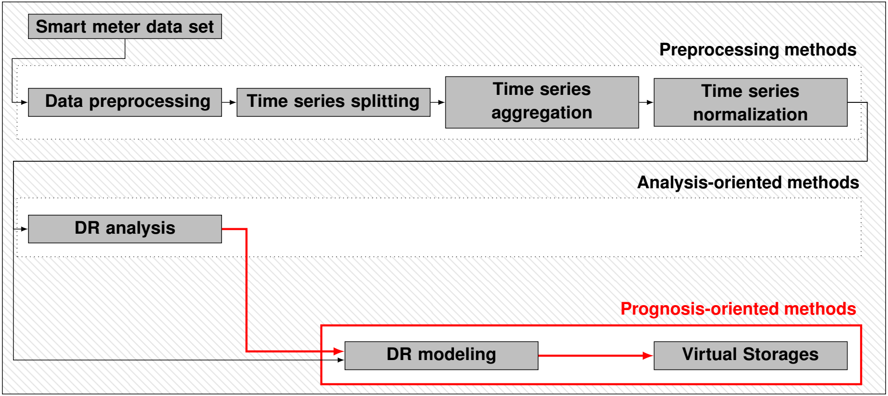
price $\rightarrow$ load reduction? price $\rightarrow$ load shifting? price $\rightarrow$ peak shaving?



2. mathematical **modeling** of consumption behaviour
   - understanding price-based consumption behaviour
   - by means of a system-theoretical approach with forecast system and price planning process
   - possibility to achieve a good model fit to real data

- **data-based modeling** of consumption behaviour of individual (aggregated) households

2.1 DR analysis and modeling concept



2.2 Analysed smart meter data set

	Olympic Peninsula Project (OPP)
Project realization	Pacific Northwest National Laboratory
Measurement period	April 2006 - March 2007
Number of households	112, Washington
Automated Demand Response	yes (e.g. residential thermostats, water heaters)

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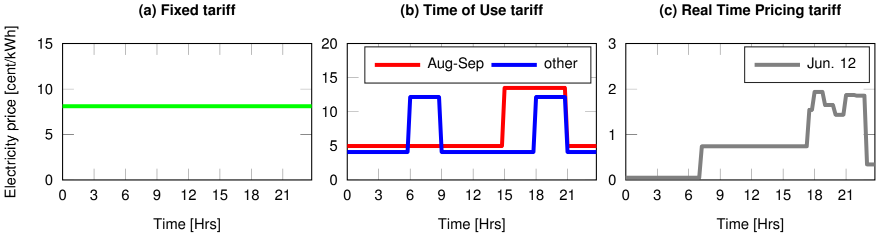
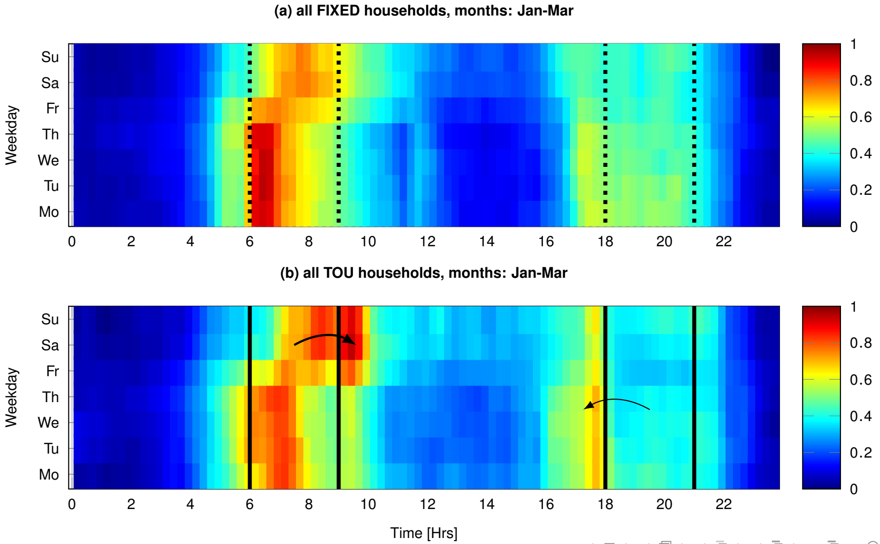
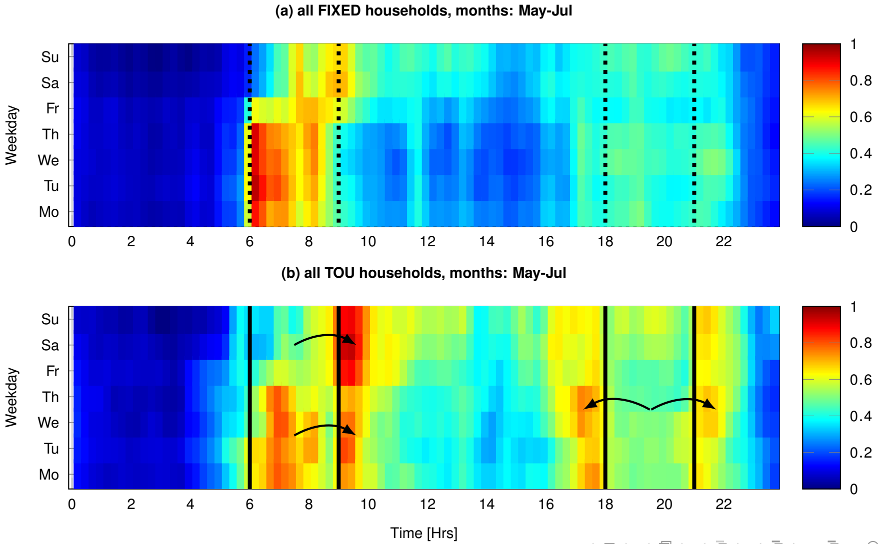
Automated Demand Response	yes (e.g. residential thermostats, water heaters)
Tariff groups	FIXED, Time of Use (TOU), Real Time Pricing (RTP)



2.3 Daily load profiles: January - March



2.3 Daily load profiles: May - July



3.1 Virtual Storage

Model requirements:

- model should describe load shifting in response to price signals
- interpretable model with a clear internal model structure

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$\rightarrow$ system of difference equations that describes load reductions/increases in response to price signals
$\rightarrow$ **grey-box model** with internal parameters (e.g. time constants, shifted energy, load shifting gradients, ...), which can be estimated
$\Rightarrow$ **Virtual Storages** as theorectically motivated Demand Response models

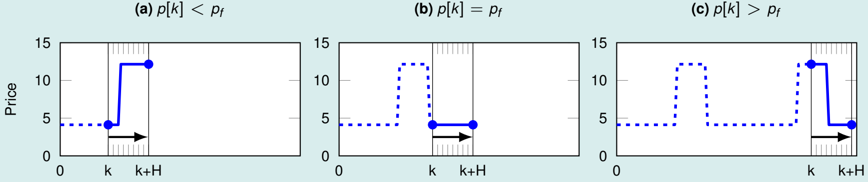
3.2 Virtual Storage: price evaluation

1. Future-oriented evaluation of electricity price:

- when future price is known (e.g. TOU)
- several methods for calculating the future price p_f:

$$p_f = p[k+H]$$
$$p_f = \text{median}(p[k+1], \ldots, p[k+H])$$
$$p_f = \text{mean}(p[k+1], \ldots, p[k+H])$$

- present price $p[k]$ is compared to future price p_f



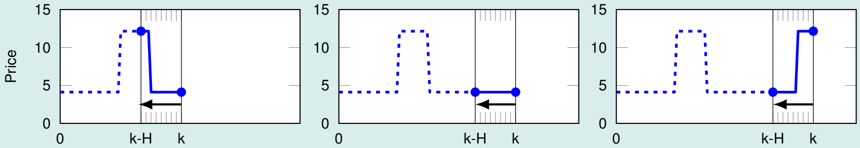
2. Backward-looking evaluation of electricity price:

- when the future price is unknown (e.g. RTP)
- several methods for calculating the past price p_p:

$$p_p = p[k-H]$$
$$p_p = \text{median}(p[k-H], \ldots, p[k-1])$$
$$p_p = \text{mean}(p[k-H], \ldots, p[k-1])$$

- present price $p[k]$ is compared to past price p_p

(a) $p[k] < p_p$ **(b)** $p[k] = p_p$ **(c)** $p[k] > p_p$



3.3 Virtual Storage A (VSA)

1. VSA, future-oriented evaluation of electricity price (e.g. TOU):

price trend	**strategy**	**equation**
$p[k] > p_f$	discharge to E_{VS}^{min}	$\hat{P}_R[k] = a \cdot (E_{VS}^{min} - E_{VS}[k])$
$p[k] = p_f$	(dis-)charge to E_{VS}^{s}	$\hat{P}_R[k] = a \cdot (E_{VS}^{s} - E_{VS}[k])$
$p[k] < p_f$	charge to E_{VS}^{max}	$\hat{P}_R[k] = a \cdot (E_{VS}^{max} - E_{VS}[k])$

$$\text{with} \quad E_{VS}[k+1] = E_{VS}[k] + \hat{P}_R[k] \cdot T_s$$

$\hat{P}_R$ - estimated load increase/decrease, T_s - sampling period in [Hrs]

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$p_p = p[k]$	(dis-)charge to E_{VS}^{s}	$\hat{P}_R[k] = a \cdot (E_{VS}^{s} - E_{VS}[k])$
$p_p < p[k]$	discharge to E_{VS}^{min}	$\hat{P}_R[k] = a \cdot (E_{VS}^{min} - E_{VS}[k])$

$$\text{with} \quad E_{VS}[k+1] = E_{VS}[k] + \hat{P}_R[k] \cdot T_s$$

$\hat{P}_R$ - estimated load increase/decrease, T_s - sampling period in [Hrs]

3.4 Virtual Storage B (VSB)

VSB, backward-looking evaluation of electricity price:

price trend	strategy	equation
$p_p > p[k]$	charge to E_{VS}^{max}	$\hat{P}_R[k] = a \cdot (1 - a_s) \cdot (E_{VS}^{max} - E_{VS}[k]) + a_s \cdot (E_{VS}^{s} - E_{VS}[k])$
$p_p = p[k]$	(dis-)charge to E_{VS}^{s}	$\hat{P}_R[k] = a \cdot (1 - a_s) \cdot (E_{VS}^{s} - E_{VS}[k]) + a_s \cdot (E_{VS}^{s} - E_{VS}[k])$
$p_p < p[k]$	discharge to E_{VS}^{min}	$\hat{P}_R[k] = a \cdot (1 - a_s) \cdot (E_{VS}^{min} - E_{VS}[k]) + a_s \cdot (E_{VS}^{s} - E_{VS}[k])$

$$\text{with} \quad E_{VS}[k+1] = E_{VS}[k] + \hat{P}_R[k] \cdot T_s$$

$\hat{P}_R$ - estimated load increase/decrease, T_s - sampling period in [Hrs]

3.5 Virtual Storage: basic structure

Real consumption behaviour	$\rightarrow$	Virtual Storage model structure	Symbol
Load gradients	$\hat{=}$	VS level change coefficient (min. or max. load changes)	a
Past load reductions/increases in response to price signals	$\hat{=}$	present level of VS as internal state variable	$E_{VS}[k]$
Amplitude of daily load	$\hat{=}$	size of VS	$E_{VS}^{max} - E_{VS}^{min}$
Load shifting over a period of maximum 24 hours	$\hat{=}$	balancing of VS level at end of day	a_s
Time when load shifting starts/ends	$\hat{=}$	observation period for price (future-oriented, backward-looking)	H

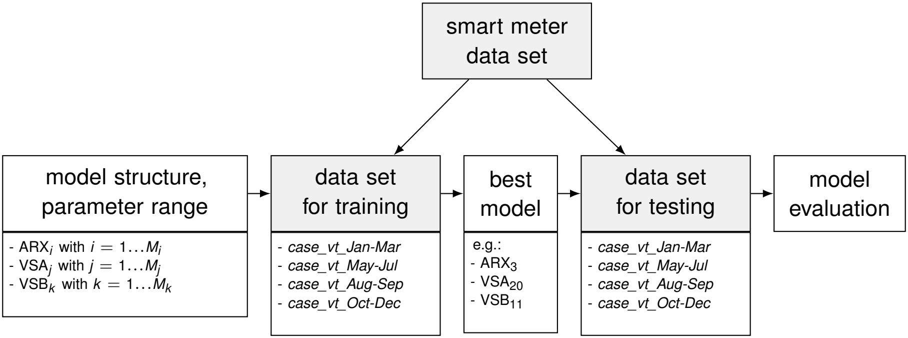
4.1 Model comparison: data set

Split OPP data set in 4 smaller data sets with variable time series lengths:

name	start date	end date	number of days (D)	missing day of year
case_vt_Jan-Mar	10-01-2007	10-03-2007	60	-
case_vt_May-Jul	05-05-2006	08-07-2006	65	156
case_vt_Aug-Sep	29-07-2006	10-09-2006	44	-
case_vt_Oct-Dec	01-10-2006	03-12-2006	64	302

4.2 Model comparison: process

Comparison of several VSX models with ARX models:



4.3 Model comparison: results

Data set for training: *case_vt_May-Jul*

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Data set for training: *case_vt_May-Jul*

data set for testing	model	R	MAE	MAE$^+$
case_vt_Jan-Mar	no	-0.010	0.195	-
case_vt_Jan-Mar	ARX	0.064	0.196	0%
case_vt_Jan-Mar	**VSA**	**0.111**	**0.195**	**0%**
case_vt_Jan-Mar	VSB	0.079	0.196	0%
case_vt_May-Jul	no	0.012	0.228	-
case_vt_May-Jul	ARX	0.259	0.228	0%
case_vt_May-Jul	VSA	0.319	0.221	3%
case_vt_May-Jul	**VSB**	**0.334**	**0.221**	**3%**

data set for testing	model	R	MAE	MAE$^+$
case_vt_Aug-Sep	no	0.004	0.207	-
case_vt_Aug-Sep	ARX	-0.065	0.214	0%
case_vt_Aug-Sep	**VSA**	**-0.015**	**0.209**	**0%**
case_vt_Aug-Sep	VSB	-0.068	0.209	0%
case_vt_Oct-Dec	no	0.001	0.217	-
case_vt_Oct-Dec	ARX	0.259	0.215	0.9%
case_vt_Oct-Dec	VSA	0.311	0.211	2.7%
case_vt_Oct-Dec	**VSB**	**0.340**	**0.210**	**3.2%**

MAE - mean absolute error, *MAE*$^+$ - improvement compared to no model, *R* - Pearson's correlation coefficient

5. Summary

- new data-driven DR analysis and modeling concept
- results of DR analysis define the structure of the *Virtual Storage* models
- *Virtual Storage* as a new theoretically motivated Demand Response model (grey-box model)

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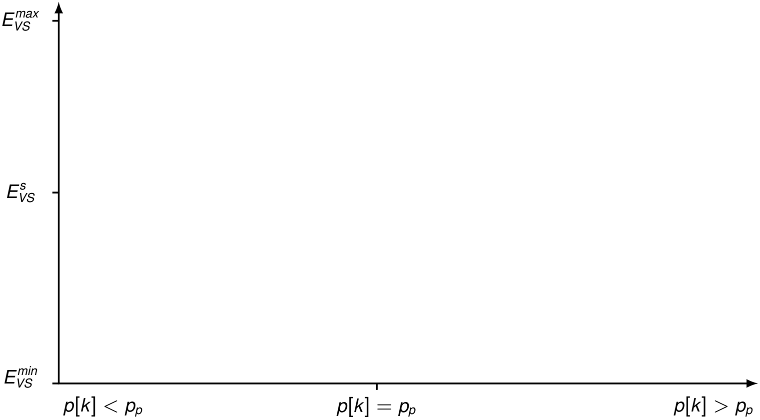
- new data-driven DR analysis and modeling concept
- results of DR analysis define the structure of the *Virtual Storage* models
- *Virtual Storage* as a new theoretically motivated Demand Response model (grey-box model)
- *Virtual Storages* are equally suitable as ARX models
- all differences between consumption groups (e.g. control group vs. TOU group) are assigned to the price influence
- other influences, like meteorological factors, are not represented in the model structure
- real smart meter data sets contain random and stochastic influences on the consumption behaviour
- well defined control group and homogeneous consumption groups in DR pilot design

Thank you for your attention

Virtual Storage: basic model behaviour in response to a price signal

Δ(present VS level[k],VS limits) $\widehat{=}$ load change potential[k] $\Rightarrow \hat{P}_R[k]$



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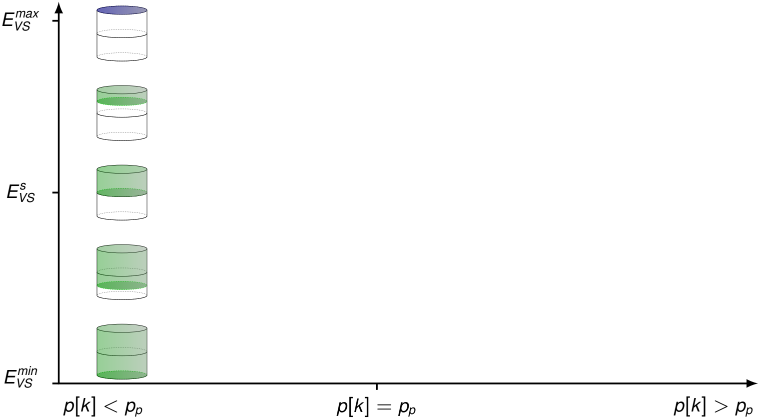

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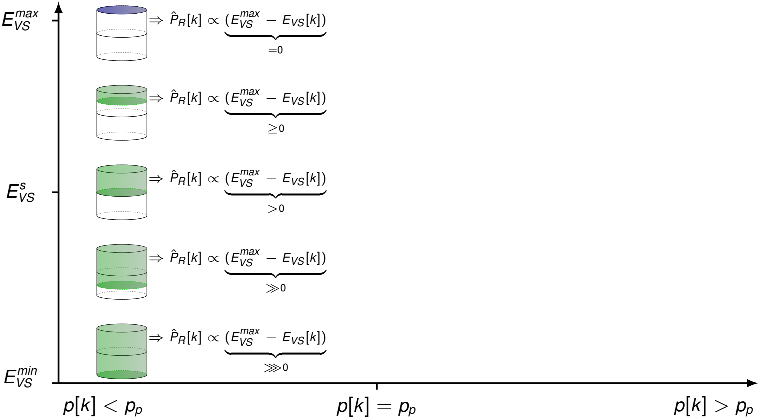

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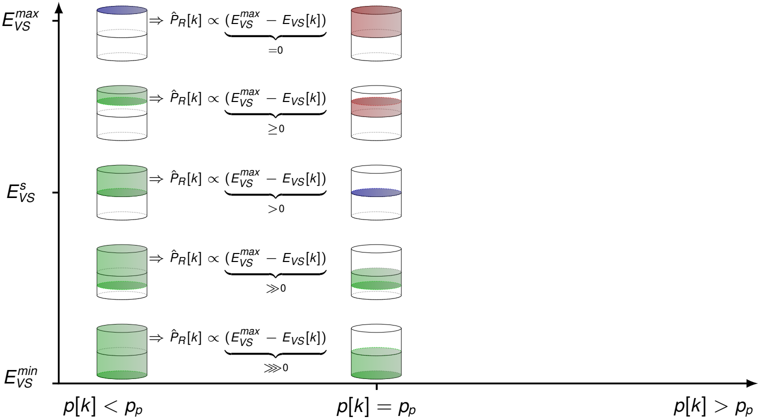

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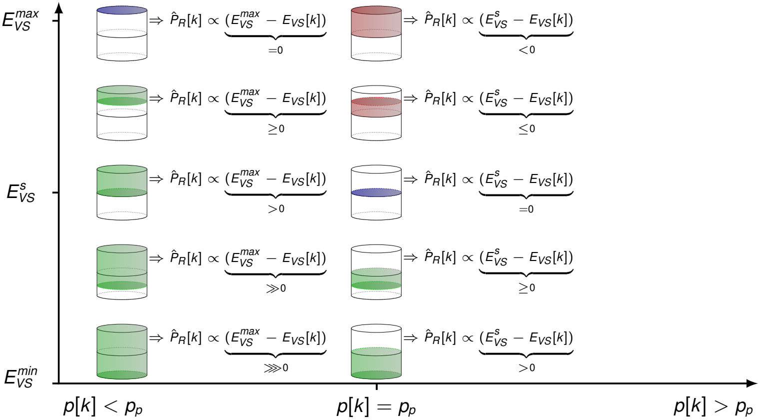

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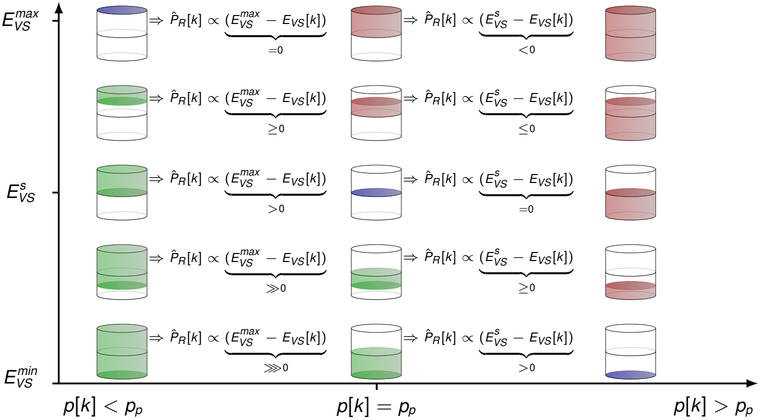

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