Consumer behaviour and residential demand side flexibility – a calibration approach for electricity load profile modelling

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Karlsruhe Institute of Technology (KIT)
Karlsruhe, Germany
Consumer behaviour and residential demand side flexibility –
a calibration approach for electricity load profile modelling

- Motivation: Residential demand side flexibility and electricity load profile modelling – why is that important?

- Methods: Electricity load profile modelling
  - Main drivers and flexible load components
  - Model introduction
  - A field trial on load shifting using variable energy prices
  - Machines vs. humans: model calibration to account for consumer behaviour

- Case study: Impact of different tariffs on demand side flexibility

- Conclusions, limitations and next steps
Expansion of renewables brings about manifold changes to the electricity system

Understanding drivers of electricity consumption profiles and impact of new tariffs on these is very important

New tariff and pricing concepts needed

- Provide demand side flexibility
- Consider changing cost structure
- Allow sustainable business models
- Ensure distributional fairness
- Beware of complexity
Tariff differentiation required considering individual consumer needs

- Analogy with internet tariffs?
- Introduction of guaranteed capacity limits
  - Curtailment option with limit
  - Capacity-based price component
- Clear definition of tangible service levels in service level agreements required to limit complexity

**Electricity tariffs**
- **Tariff A**
  - Minimum guaranteed capacity limit: low
  - Base price: low
  - Illustrative electricity services: Min. 1 large appliance (~3.000 W)
- **Tariff B**
  - Minimum guaranteed capacity limit: medium
  - Base price: medium
  - Illustrative electricity services: Min. 2 large appliances (~6.000 W)
- **Tariff C**
  - Minimum guaranteed capacity limit: high
  - Base price: high
  - Illustrative electricity services: Many large appliances (~20.000 W)

**Internet tariffs**
- **Tariff A**
  - Download speed: low
  - Base price: low
- **Tariff B**
  - Download speed: medium
  - Base price: medium
- **Tariff C**
  - Download speed: high
  - Base price: high

Illustrative download speed:
- 16 Mbit/s
- 32 Mbit/s
- 100 Mbit/s

Woo et al. (2014), Hayn et al. (2015)
**Bottom-up electricity load profile model with load flexibility: Schematic structure**

**Load profile simulation**
- Considering season and time of day
- Times and frequencies of utilisation vary between weeks and between appliances
- Yearly load profiles for each household and appliance

**Demand side flexibility**
- Tariff incentive (AP/LP) an solar PV own consumption
- Automated and manual load shifting of selected appliances (optimisation)

**Appliance equipment, characteristics and utilisation**
- Fridge
- Freezer
- Washing machine
- Tumble dryer
- Dishwasher
- El. stove
- TV
- DVD/Video
- Audio
- PC/Laptop
- ICT
- Lighting
- Circulation pump
- Night storage heater
- Hot water (direct)
- Hot water (Storage)
- Other

**Data**
- Statistical data, published reports and papers, assumptions

**Distribution functions**
- Averages

**Coupling**
- Households
  - HH size
  - Tariff
    - EP (var./ fix)
    - CP (var./ fix)

**Motivation**

**Methods**

**Case study**

**Conclusions**

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EP = Energy Price (€/kWh); CP = Capacity Price (€/kW); var. = variable

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*Hayn et al. (2016)*
Bottom-up electricity load profile model with load flexibility: 3 essential steps

Generation and initialisation of households

Start
Read input
Generate household
i = 0
i++

Data

i < |I|?

yes

no

1

Generation of weekly load profiles

Simulate and optimise weekly load profiles
i < |I|?

yes

no

Data

w = 0
w++
i = 0
i++

Generation of yearly load profiles

Generate yearly load profiles
Determine consumption characteristics
Write Output

Ene

2

Core of the model

$I = \text{Households}; W = \text{Weeks}$

Hayn et al. (2016)
Bottom-up electricity load profile model with load flexibility: Simulation of appliance utilisation

Simulation and optimisation of weekly profiles

- Start
- Simulate appliance utilisation
  - Optimise with variable energy prices
  - Optimise with variable capacity prices
  - Generate weekly load profile
- End

Model essentials

- Determine appliance usage **frequency** within week
- Determine appliance usage **start(s)**
- Calculate **electricity demand** over time
Bottom-up electricity load profile model with load flexibility: Appliance optimisation with variable energy prices

Simulation and optimisation of weekly profiles

- Start
  - Simulate appliance utilisation
  - Optimise with variable energy prices
  - Optimise with variable capacity prices
  - Generate weekly load profile
  - End

Model essentials

- Target function: **Minimise costs** of electricity usage
  \[
  \min_{t \in \{t_{w,g,u}^{\min}, ..., t_{w,g,u}^{\max}\}} c_{w,t,g,u} \\
  \forall g \in G^{\text{FlexActive}}, u \in U_{w,g}, w \in W
  \]

- Cost function for active appliances
  \[
  c_{w,t,g,u} = \frac{1}{4} \sum_{d=0}^{D_g-1} \left( q_{w,(t+d),g,u}^{PV} \cdot \varphi_{w,t}^{PV} + (\psi_{g,d} \cdot \lambda_{g}^{\max} - q_{w,(t+d),g,u}^{PV}) \cdot \varphi_{w,(t+d)}^{Tariff} \right) \\
  \forall t \in \{t_{w,g,u}^{\min}, ..., t_{w,g,u}^{\max}\}, g \in G^{\text{FlexActive}}, u \in U_{w,g}, w \in W
  \]

- Supply of solar PV modules
  \[
  q_{w,t,g,u}^{PV} = \max \left( 0, \min \left( \nu_{w,t} - \sum_{g \in G} \sum_{u \in U_{w,g}} \hat{q}_{w,t,g,u} \cdot \lambda_{g}^{\max} \right) \right) \\
  \forall t \in \{0,1, ..., |T_w|\}, g \in G^{\text{Flex}}, u \in U_{w,g}, w \in W
  \]

**Parameters & Variables:**
- \( c \): costs; \( D \): appliance usage duration; \( q \): el. load; \( \varphi \): price; \( \lambda \): power consumption; \( \nu \): available power from PV system; \( \psi \): load factor; \( \text{Index sets} \): \( G \): appliances; \( T \): time steps; \( U \): appliance usage frequencies; \( W \): weeks; Other indeces: \( d \): time step of usage; \( \text{Flex} \): manually or automatically shiftable; \( \text{max} \): upper limit / max.; \( \text{min} \): lower limit / min; Special characters: ``: appliance type; `~`: value already simulated
Bottom-up electricity load profile model with load flexibility: Optimisation with variable capacity prices

Simulation and optimisation of weekly profiles

- **Start**
- **Data**
  - Simulate appliance utilisation
- **Optimise with variable energy prices**
- **Optimise with variable capacity prices**
- **Generate weekly load profile**
- **End**

Model essentials

- **Target function**: Minimise costs of capacity limit penalties and reduction of comfort losses

\[
\min \left( \sum_{t=t_{w,s}^{\min}}^{t_{w,s}^{\max}} \left( \tau_{\text{T tariff}} b_{w,t,s}^{\text{T tariff}} + \sum_{g \in G}^{\text{Flex}} \sum_{u \in U_{w,g}}^{\text{Flex}} \tau_{g}^{\text{Flex}} b_{w,t,s,g,u}^{\text{Flex}} \right) \right)
\]

- **Constraint for capacity limit**

\[
\left( \sum_{g \in G}^{\text{Flex}} \sum_{u \in U_{w,g}}^{\text{Flex}} q_{w,t,g,u} \right) - \gamma_{w,t}^{\max} \leq b_{w,t,s}^{\text{T tariff}} * M^{\text{T tariff}}
\]

\[\forall t \in \{t_{w,s}^{\min}, ..., t_{w,s}^{\max}\}, s \in S_w, w \in W\]

- **Determination of capacity limit**

\[
\gamma_{w,t}^{\max} = \gamma_{w,t}^{\text{T tariff}} + \gamma_{w,t}^{\max} \ \forall t \in \{0,1, ..., |T_w|\}, w \in W
\]

Parameters & Variables: 
- \( b \): binary variable; \( M \): Big M parameter; \( q \): el. load; \( \gamma \): guaranteed capacity limit; \( \tau \): penalty term; \( \nu \): available power from PV system; 
- Index sets: \( G \): appliances; \( S \): shortage situations; \( T \): time steps; \( U \): appliance usage frequencies; \( W \): weeks; 
- Other indices: \( \text{Flex} \): manually or automatically shiftable; \( \text{max} \): upper limit / max.; \( \text{min} \): lower limit / min; 
- Special characters: \( \cdot \): appliance type

Hayn et al. (2016)
Backtesting of the model shows good performance on an aggregated level

On an individual household level, large deviations may occur
On an aggregated level, the model produces very good results (without behavioural components)
Accounting for behavioural aspects seems much more relevant when tariff and pricing schemes are changed (‘machine-based’ load modelling works well for standard tariff)

### Comparison of simulation results and standard load profiles ("VDEW H0")

- Aggregated profile of 1000 households vs. SLP (summer week working day)

### Selected characteristics

<table>
<thead>
<tr>
<th># of simulated households</th>
<th>Correlation simulation vs. SLP</th>
<th>RMSE [W]</th>
<th>NRMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0,203</td>
<td>162,3</td>
<td>6,1 %</td>
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<tr>
<td>10</td>
<td>0,652</td>
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<td>1000</td>
<td>0,929</td>
<td>17,5</td>
<td>7,4 %</td>
</tr>
</tbody>
</table>

**SLP** = Standard Load Profile; **RMSE** = Root Mean Square Error; **NRMSE** = Normalized Root Mean Square Error

Sources: Fünfgeld & Tiedemann (2000); Hillemacher (2014); Hayn et al. (2016)
Load shifting behaviour and its main influencing factors were analysed in a long-term field trial in Germany.

Results show that...
- load shifting is incentivised
- general saving effects can be observed (increased awareness)

Flexibility in each hour depends on...
- season, day of week, time of day
- tariff level in adjacent hours

Duration: Nov 2009 - Sep 2012
Approx. 1000 test customers
More than 75% of the test customers reacted on a purely manual basis
Model calibration using field trial data: Replication of load shifting behaviour observed in the field trial

Calibration approach

- Machines vs. humans: ranges (see right hand side) represent min. and max. load shifting potential achievable within the model
  - Min: Only the existing **smart appliances** react on price signals
  - Max: All households manually optimise all utilisations of dish washers, washing machines and tumble dryers (= automatic shifting)
- Calibration through probabilities for hourly Bernoulli distributions (depending on season, day of week and time of day) ranging…
  - … from 0: no manual load shifting
  - … to 1: full manual load shifting

Calibration results

- No single possible answer
- Chosen calibration parameters consider uncertainties and self selection in field trial
- Probabilistic determination whether utilisation of dishwashers, washing machines or tumble dryers is shifted manually

<table>
<thead>
<tr>
<th>Calibration results</th>
<th>Load shifting [%]</th>
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</thead>
<tbody>
<tr>
<td>SNT</td>
<td>5.7%</td>
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<tr>
<td>NT</td>
<td>6.1%</td>
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<tr>
<td>HT</td>
<td>-1.2% - -1.5% -4.3%</td>
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<tr>
<td>Model</td>
<td></td>
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<tr>
<td>MeRegio field trial</td>
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<tr>
<td>Possible range</td>
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</table>

SNT = Low tariff; NT = Moderate tariff; HT = High tariff
Sources: Hillemacher (2014); Hayn et al. (2016)
Derived hourly probabilities for the Bernoulli distributions of manual load shifting

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
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</table>
### Analysing the impact of different tariffs on residential demand side flexibility in 4 scenarios

<table>
<thead>
<tr>
<th># of simulated households</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distribution of household size</strong></td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>Individual, e.g. specific household sizes</td>
</tr>
<tr>
<td><strong>Appliance equipment</strong></td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>Individual (without heating appliances)</td>
</tr>
<tr>
<td><strong>Share of smart appliances</strong></td>
<td></td>
</tr>
<tr>
<td>0 %</td>
<td>25 %</td>
</tr>
<tr>
<td><strong>Share of households with solar PV</strong></td>
<td></td>
</tr>
<tr>
<td>0 %</td>
<td>Status quo</td>
</tr>
<tr>
<td><strong>Energy price</strong></td>
<td></td>
</tr>
<tr>
<td>Fix</td>
<td>MeRegio</td>
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<tr>
<td><strong>Capacity price</strong></td>
<td></td>
</tr>
<tr>
<td>Fix</td>
<td>Variable</td>
</tr>
</tbody>
</table>

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Valentin Bertsch
13.07.2016

Hayn et al. (2016)
Model results show clear impact of variable energy and/or capacity prices on electrical load

Tariff impact on electrical load of households

Tariff impact on electrical load during shortage situations

- **Variable capacity prices** have a limited impact in comparison to status quo load profiles
- **Variable energy prices** bring about new load peaks

- **Variable capacity prices** offer a limited but more dependable load shifting potential
- **Variable energy prices** may lead to (partly) undesired load increase

Lower variability of load change for variable capacity prices, particularly during shortage situations, leads to higher predictability in comparison to variable energy prices

Valentin Bertsch
Zooming in on a summer Sunday helps illustrating the different impacts of the tariffs.

**Summer Sunday with shortages**

**Variable energy prices**
- Higher load change
- (Small) undesired load increase resulting from small change(s) in the energy price

**Variable capacity prices**
- Rather constant load change of approx. -2%

**Main reasons**
- Energy prices apply to all simulated households
- Load curtailment only applies to households above certain pre-defined capacity limits
Conclusions, limitations and next steps

**Conclusions**
- New market, tariff and pricing concepts needed
- Considered tariffs leverage demand side flexibility
- Tariff with variable capacity price brings about lower variability, thus higher predictability of demand side flexibility
- Regulatory adjustments needed to create incentives for suppliers to offer new tariffs
- Technical infrastructure requirements for the considered tariffs should be taken into account before smart meter roll-out

**Model) Limitations**
- Underestimation of load peaks as a result of 15-min time resolution
- Not all high-capacity appliances included in the model
- Simplified consideration of thermal storage possibilities
- No interdependencies / feedback loops between households and system considered
- Elementary calibration approach

**Next steps**
- Welfare and distributional analysis
- Tariff choice experiments
- Further field trial: investigate energy usage behaviour for different tariffs
- Model improvement (see left, particularly including behaviour)
- Explore impact of demand side flexibility induced by different tariffs on long-term system development (including investments into new capacities)
References


Thank you very much for your attention!

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