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

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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

Expansion of renewable energy sources (RES)

Increasing volatility of system residual load

Increasing **flexibility** requirements

Changes in cost structure: increasing share of (fix) infrastructure costs (grid, storage...)

Markets (today based on marginal variable costs; meaning in a system with only RES and storage?)

Changes in electricity value chain (particularly PV, self generation...)

Suppliers (business model of generating and selling kWh not sustainable)

Society (system charges on a per kWh basis, people who can afford self generation contribute less...)

New tariff and pricing concepts needed

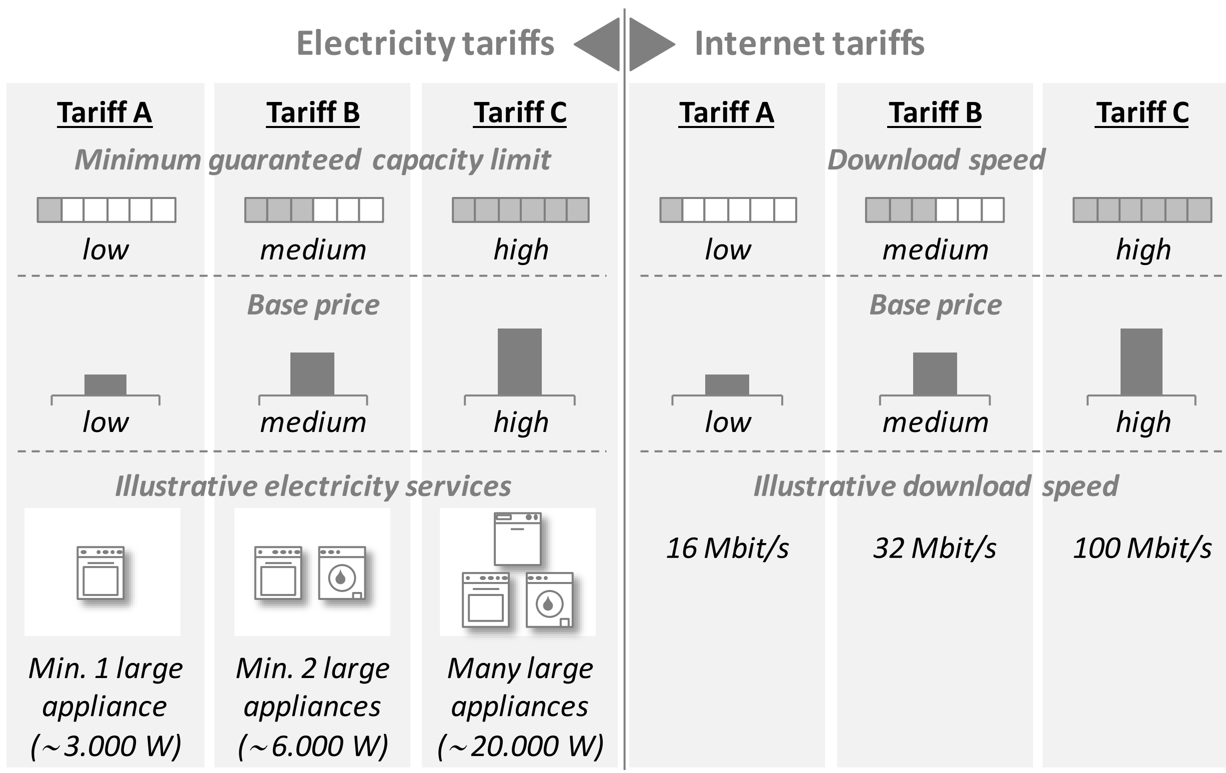
- Provide demand side flexibility
- Consider changing cost structure
- Allow sustainable business models
- Ensure distributional fairness

- Beware of complexity

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

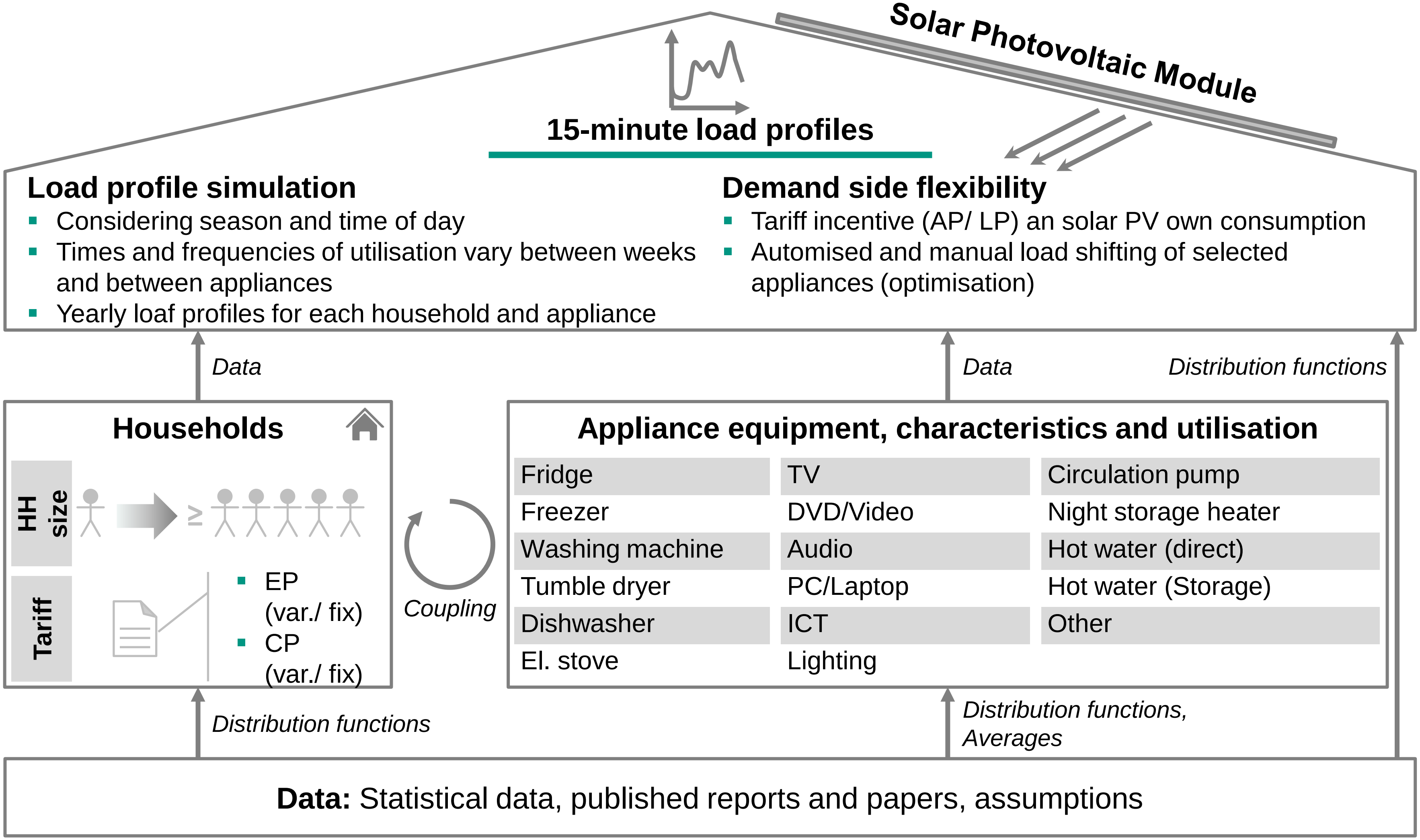
Tariff differentiation required considering individual consumer needs

- 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



Woo et al. (2014), Hayn et al. (2015)

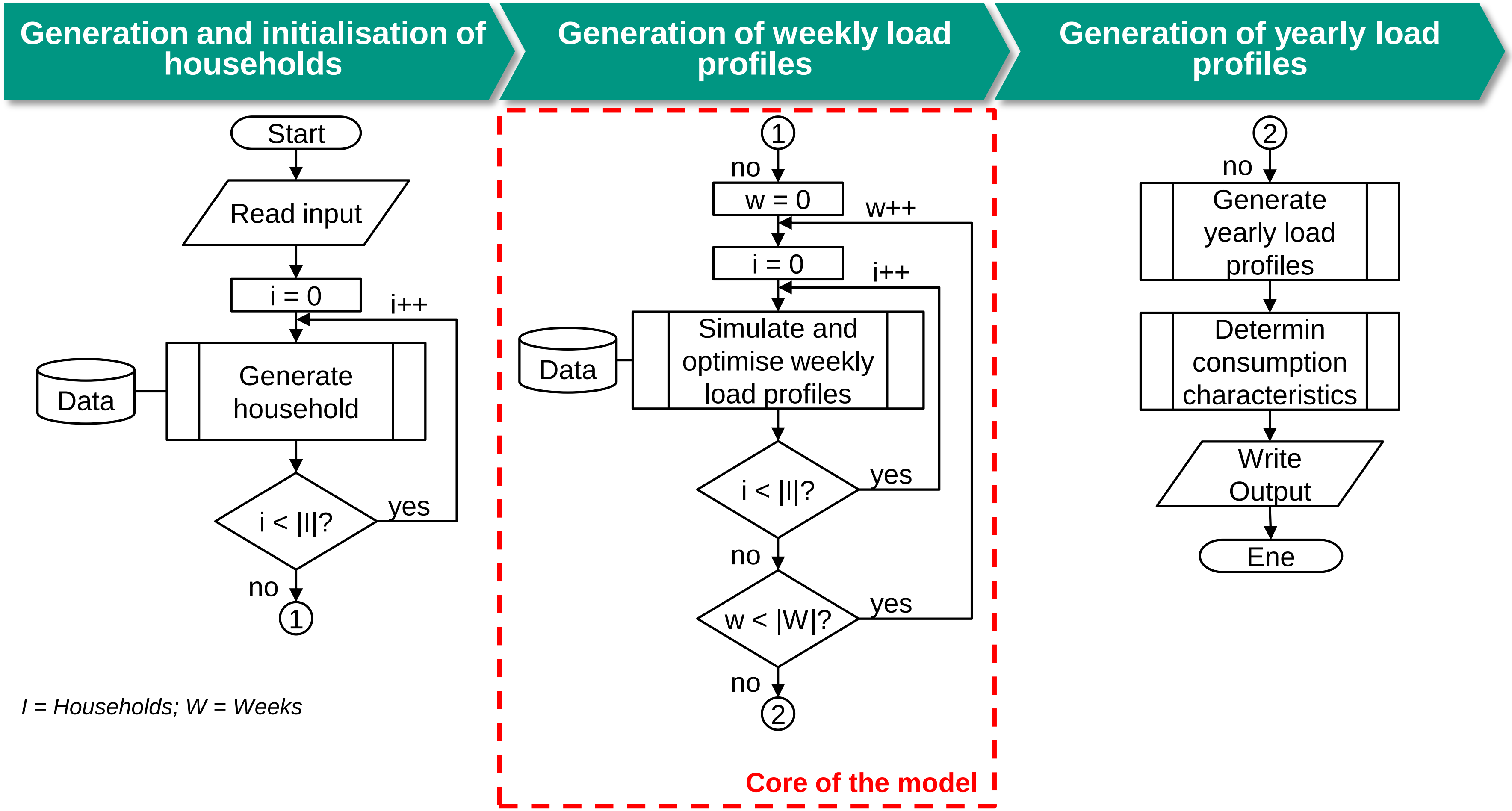
Bottom-up electricity load profile model with load flexibility: Schematic structure



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

Hayn et al. (2016)

Bottom-up electricity load profile model with load flexibility: 3 essential steps

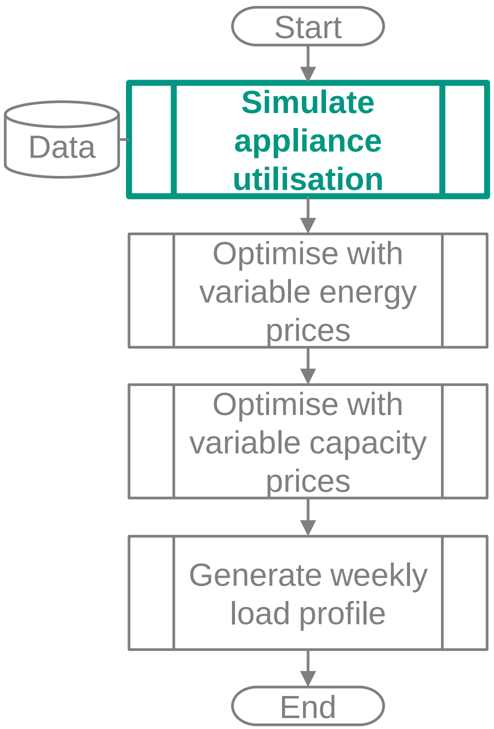


I = Households; W = Weeks

Hayn et al. (2016)

Bottom-up electricity load profile model with load flexibility: Simulation of appliance utilisation

Simulation and optimisation of weekly profiles



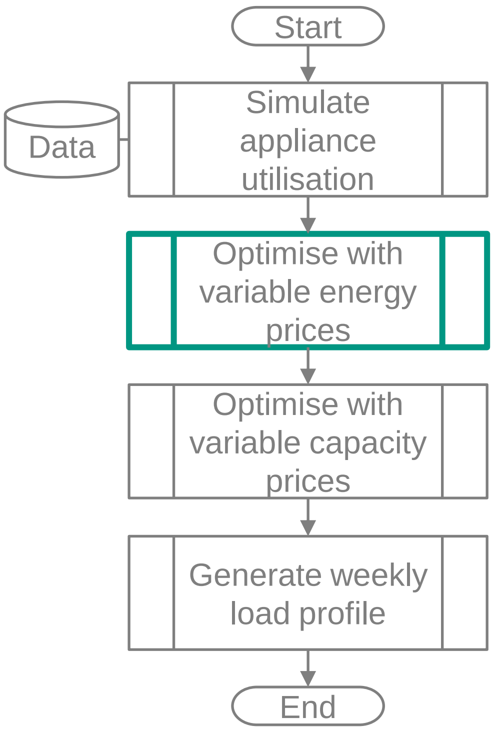
Model essentials

- Determine appliance usage **frequency** within week
- Determine appliance usage **start(s)**
- Calculate **electricity demand** over time

Hayn et al. (2016)

Bottom-up electricity load profile model with load flexibility: Appliance optimisation with variable energy prices

Simulation and optimisation of weekly profiles



Model essentials

- Target function: **Minimise costs** of electricity usage

$$\min_{t\in\{t^{min}_{w,g,u},\dots,t^{max}_{w,g,u}\}} c_{w,t,g,u}$$

$$\forall g\in G^{FlexActive}, u\in U_{w,g}, w\in W$$

- Cost function for **active appliances**

$$c_{w,t,g,u} = \frac{1}{4}\sum_{d=0}^{D_{\dot{g}}-1}\left(q^{PV}_{w,(t+d),g,u} * \varphi^{PV} + \left(\psi_{\dot{g},d} * \lambda^{max}_{g} - q^{PV}_{w,(t+d),g,u}\right) * \varphi^{Tariff}_{w,(t+d)}\right)$$

$$\forall\, t \in \{t^{min}_{w,g,u}, \dots, t^{max}_{w,g,u}\}, g \in G^{FlexActive}, u \in U_{w,g}, w \in W$$

- **Supply of solar PV modules**

$$q^{PV}_{w,t,g,u} = max\left(0, min\left(\nu_{w,t} - \sum_{g\in\tilde{G}}\sum_{u\in\tilde{U}_{w,g}} \tilde{q}_{w,t,g,u}, \lambda^{max}_{g}\right)\right)$$

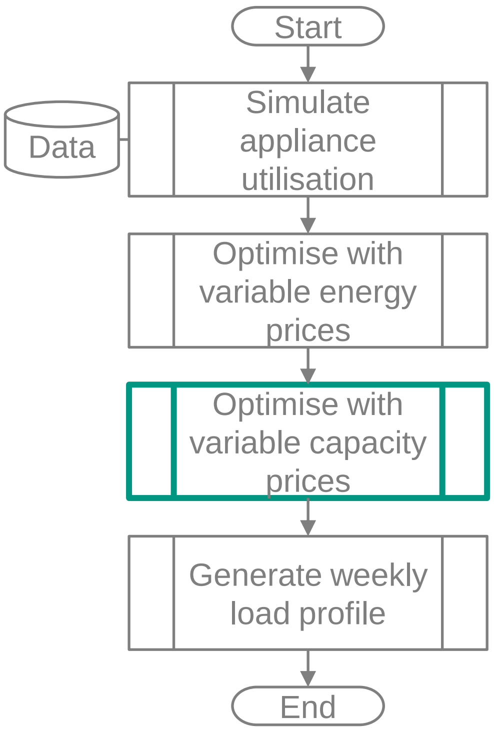
$$\forall\, t \in \{0,1,\dots,|T_w|\}, g \in G^{Flex}, u \in U_{w,g}, w \in W$$

Parameters & Variables: c: costs; D: appliance usage duration; q: el. load; φ: price; λ: power consumption; ν: available power from PV system; ψ: load factor; **Index sets:** G: appliances; T: time steps; U: appliance usage frequencies; W: weaks; **Other indeces:** d: time step of usage; $Flex$: manually or automatically shiftable; max: upper limit / max.; min: lower limit / min; **Special characters:** $\dot{}$: appliance type; $\tilde{}$: value already simulated

Hayn et al. (2016)

Bottom-up electricity load profile model with load flexibility: Optimisation with variable capacity prices

Simulation and optimisation of weekly profiles



Model essentials

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

$$\min_{\substack{(b^{Tariff}_{w,t,s},\, b^{Flex}_{w,t,s,g,u}) \\ \forall s\in S_w,\, w\in W}} \left(\sum_{t=t^{min}_{w,s}}^{t^{max}_{w,s}} \left(\tau^{Tariff} * b^{Tariff}_{w,t,s} + \sum_{g\in G^{Flex}} \sum_{u\in U_{w,g}} \tau^{Flex}_{\dot{g}} * b^{Flex}_{w,t,s,g,u} \right) \right)$$

- Constraint for **capacity limit**

$$\left(\sum_{g\in G} \sum_{u\in U_{w,g}} q_{w,t,g,u} \right) - \gamma^{max}_{w,t} \le b^{Tariff}_{w,t,s} * M^{Tariff}$$

$$\forall\, t \in \{t^{min}_{w,s}, \dots, t^{max}_{w,s}\}, s \in S_w, w \in W$$

- Determination of capacity limit

$$\gamma^{max}_{w,t} = \gamma^{Tariff}_{w,t} + \nu^{max}_{w,t} \quad \forall\, t \in \{0,1,\dots,|T_w|\}, w \in W$$

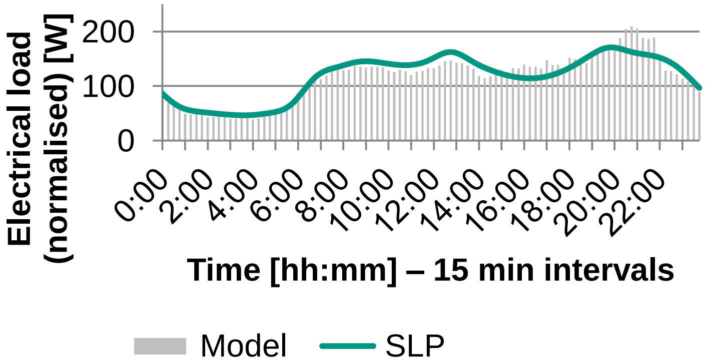
Parameters & Variables: *b*: binary variable; *M*: Big M parameter; *q*: el. load; γ: guaranteed capacity limit; τ: penalty term; *ν*: available power from PV system; **Index sets:** *G*: appliances; *S*: shortage situations; *T*: time steps; *U*: appliance usage frequencies; *W*: weaks; **Other indeces:** *Flex*: manually or automatically shiftable; *max*: upper limit / max.; *min*: lower limit / min; **Special characters:** ˙ : appliance type

Hayn et al. (2016)

Backtesting of the model shows good performance on an aggregated level

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

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



Selected characteristics

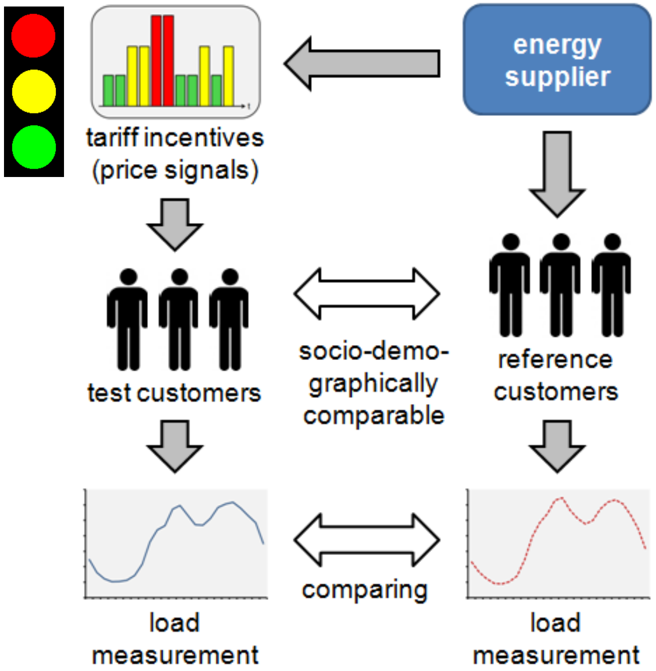
# of simulated households	Correlation simulation vs. SLP	RMSE [W]	NRMSE
1	0,203	162,3	6,1 %
10	0,652	52,8	9,4 %
100	0,895	22,7	7,5 %
1000	0,929	17,5	7,4 %

- 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)

SLP = Standard Load Profile; RMSE = Root Mean Square Error; NRMSE = Normalized Root Mean Sqaure Error
Sources: Fünfgeld & Tiedemann (2000); Hillemacher (2014); Hayn et al. (2016)

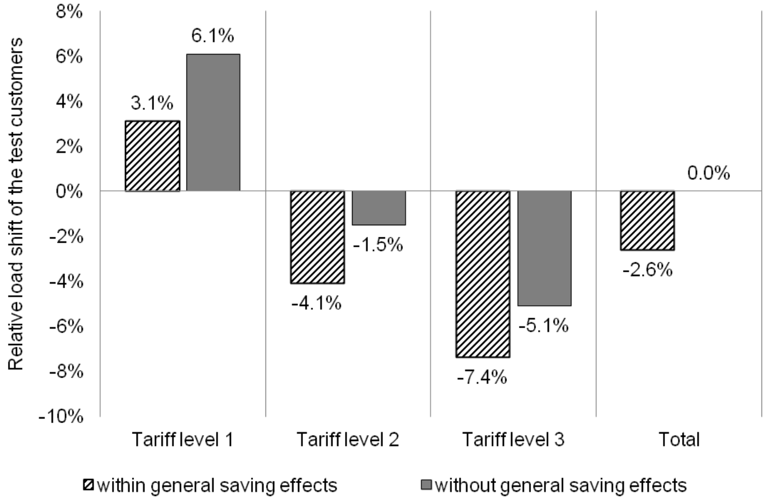
Load shifting behaviour and its main influencing factors were analysed in a long-term field trial in Germany

Conduction of a field trial using variable energy prices



- Duration: Nov 2009 - Sep 2012
- Approx. 1000 test customers
- More than 75% of the test customers reacted on a purely manual basis

Selected results of the field trial



- 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

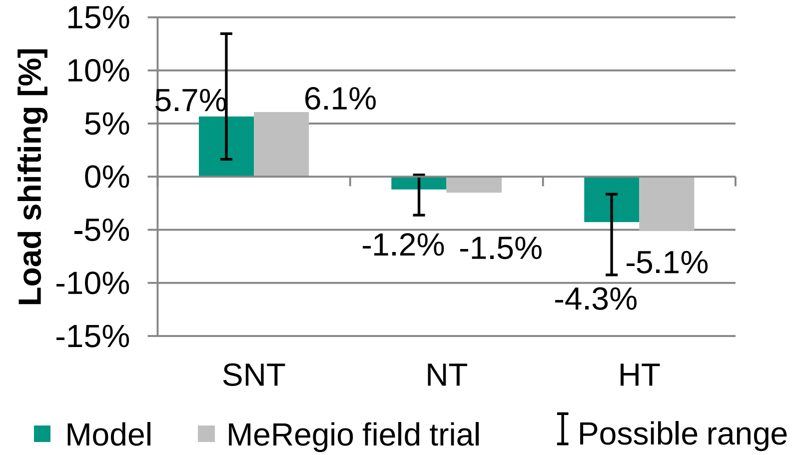
Hillemacher (2014)

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

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

	Winter			Summer			Transition		
	Mo.-Fr.	Sa.	Su.	Mo.-Fr.	Sa.	Su.	Mo.-Fr.	Sa.	Su.
0	10%	10%	10%	10%	10%	10%	10%	10%	10%
1	10%	10%	10%	10%	10%	10%	10%	10%	10%
2	10%	10%	10%	10%	10%	10%	10%	10%	10%
3	10%	10%	10%	10%	10%	10%	10%	10%	10%
4	10%	10%	10%	10%	10%	10%	10%	10%	10%
5	20%	20%	20%	20%	20%	20%	20%	20%	20%
6	20%	20%	20%	20%	20%	20%	20%	20%	20%
7	50%	40%	40%	30%	30%	30%	30%	30%	30%
8	50%	40%	40%	30%	30%	30%	30%	30%	30%
9	50%	40%	50%	30%	30%	30%	30%	30%	30%
10	50%	40%	50%	40%	30%	40%	40%	30%	40%
11	50%	40%	50%	40%	30%	40%	40%	30%	40%
12	50%	50%	50%	40%	30%	40%	40%	30%	40%
13	50%	50%	50%	40%	30%	40%	40%	30%	40%
14	50%	50%	50%	40%	30%	40%	40%	30%	40%
15	50%	40%	50%	40%	30%	40%	40%	30%	40%
16	50%	40%	50%	40%	30%	40%	40%	30%	40%
17	40%	40%	40%	30%	30%	30%	30%	30%	30%
18	40%	40%	40%	30%	30%	30%	30%	30%	30%
19	30%	30%	30%	20%	20%	20%	20%	20%	20%
20	30%	30%	30%	20%	20%	20%	20%	20%	20%
21	20%	20%	20%	20%	20%	20%	20%	20%	20%
22	10%	10%	10%	10%	10%	10%	10%	10%	10%
23	10%	10%	10%	10%	10%	10%	10%	10%	10%

Hayn et al. (2016)

Analysing the impact of different tariffs on residential demand side flexibility in 4 scenarios

# of simulated households	**1000**				
Distribution of household size	**Germany**	Individual, e.g. specific household sizes			
Appliance equipment	Germany	**Individual (without heating appliances)**			
Share of smart appliances	0 %	25 %	**50 %**	75 %	100 %
Share of households with solar PV	**0 %**	Status quo	Expansion		
Energy price	**Fix**	MeRegio	**EPEX**		
Capacity price	**Fix**	**Variable**			

Status quo

Variable capacity prices (var. CP)

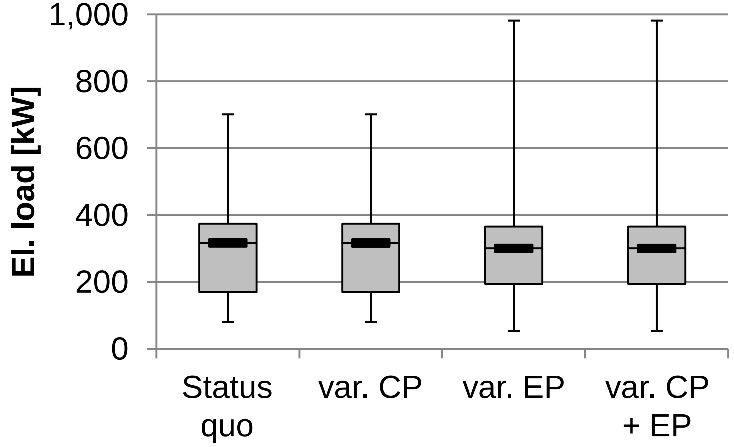
Variable energy prices (var. EP)

Variable energy and capacity prices (var. EP + CP)

Hayn et al. (2016)

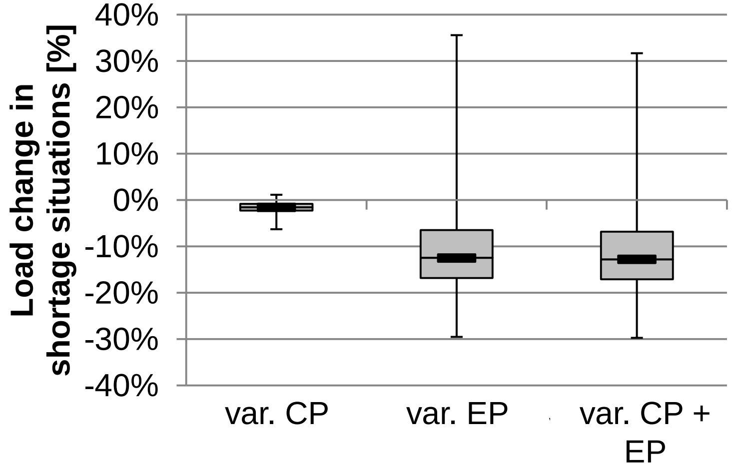
Model results show clear impact of variable energy and/or capacity prices on electrical load

Tariff impact on electrical load of households



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

Tariff impact on electrical load during shortage situations

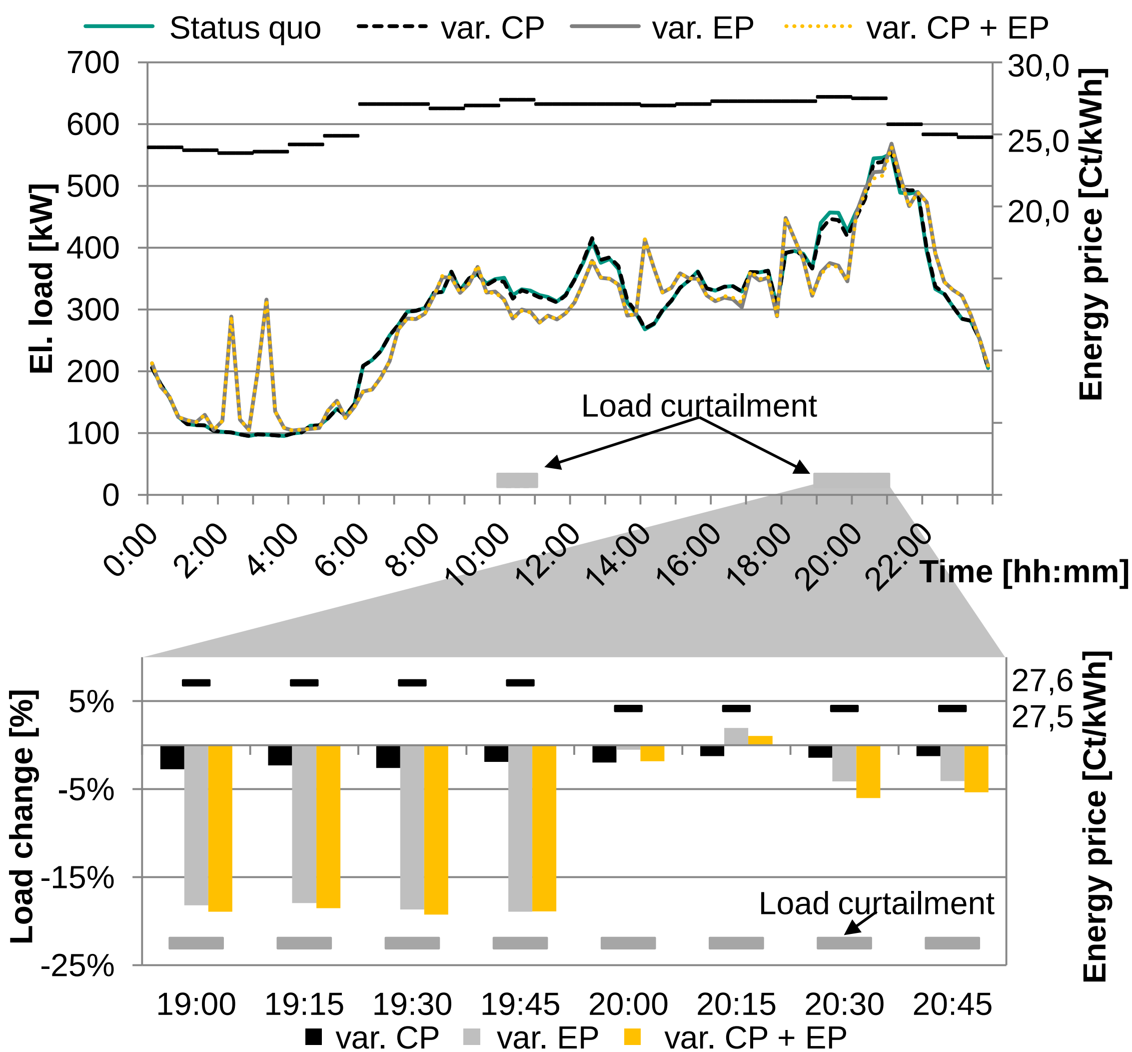


- **Variable capacity prices** offer a limited but more dependable load shifting potential
- **Variable energy prices** may lead to (partly) undesired load increase

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

Hayn et al. (2016)

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

Hayn et al. (2016)

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)

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Thank you very much for your attention!

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