APPENDIX

Appendix A. Literature Review

	Regulatory system	Tariff design	Net-metering type	Causal link/loop investigated	Diffusion of PV	Behavioral aspects	Prosumer communi-ties, storage	Cost recovery of grid	Cost recovery feedback loop	Distributi on effect
Darghouth et al. (2011), Darghouth et al. (2014), Darghouth et al. (2016a)	Integrated (California, USA)	Volumetric	Net-metering (various rolling credit timeframes)	Effect of net-metering design (Darghouth et al., 2011) and market design (Darghouth et al., 2016a) on PV bill-savings and wholesale electricity price (Darghouth et al., 2014)	No	No	No	**G**	**H**	**I**
Cai et al. (2013)	Integrated (USA, California)	Volumetric	Net-metering	Cost recovery feedback loop	Yes	Yes	No	No	No	No
Costello and Hemphill (2014)	Integrated (generic, USA)	Volumetric	Net-metering	Influence of PV penetration on utility cost recovery	(Yes), elasticity of demand	No	No	Yes	Yes	No
Eid et al. (2014)	Unbundling (Europe, Spain)	Volumetric, capacity, flate rate	Net-metering (various rolling credit timeframes)	Effect of net-metering design on PV bill-savings and cross-subsidization	No	No	Yes, storage	Yes	No	No
Grace (2014)	Integrated (Australia)	Volumetric	Renewable Energy Buyback System	Death spiral, duck curve, grid capacity	Yes	No	Yes, storage	No	No	Yes
Darghouth et al. (2016b)	Integrated (USA)	Volumetric	Net-metering	Fixed-cost recovery feedback vs. time-varying electricity price feedback	Yes	No	No	Yes	Yes	No
Target of this paper	Unbundling	Volumetric, capacity	Net-metering, net purchase and sale	Cost recovery feedback loop, cost-causality	Yes	Yes	Yes	Yes	Yes	No

Table 1: Review of the existing literature on quantitative approaches on the cost recovery of distribution grids

Appendix B. General Simulation settings

The model was implemented in the Software Vensim DSS, Version 6.4E. Model settings are described in Table 5.

Initial time	2009
Final time	2050
Time step	0.0078125
Units for Time	Year
Integration Type	Euler

Table 2: Model settings in Vensim

The simulations and optimizations were executed on a DELL Latitude E7270 laptop. No significant computing costs are needed. The simulation and optimization time are below one minute.

Exogenous data was imported through CIN files, to allow easy exchange of the data sets for the different simulated regions.

Appendix C. Data inputs

In Table 6 the most relevant data inputs are presented. For a complete list I refer to the delivered supporting material, where also all data sources and transformation are documented.

Variable	**Value / Initial value**
Population [people]	824’054
Grid consumers, single-family houses [houses]	166’600
Grid consumers, multi-family houses [houses]	23’280
Grid consumers, commercial consumers [houses]	8’206
Prosumers, single-family houses [houses]	0
Prosumers, multi-family houses [houses]	0
Prosumers, commercial consumers [houses]	0
Storage prosumers, single-family houses [houses]	0
Storage prosumers, multi-family houses [houses]	0
Storage prosumers, commercial consumers [houses]	0
Total PV potential [kW]	535’100
PV potential, single-family houses [kW]	308’200
PV potential, multi-family houses [kW]	100’600
PV potential, commercial customers [kW]	126’300

sr, share of roofs suitable for PV [Dmnl]	0.32
Power generation per kW of installed PV [kWh/kW]	1024
Power price [CHF/kWh] (from 2016, before historical data)	0.0897
taxes on electricity [CHF]	0.015
Annual growth of total grid costs [Dmnl]	0.03
Price for PV power [CHF/kWh]	0.165
Costs per measuring unit [CHF/a]	123
Average number of measuring units needed for a multi-family house [Dmnl]	5.4
Initial total grid costs [CHF/a] (historical data is used)	217’354’163

Table 3: Data inputs for the simulations

Appendix D. Optimization settings to determine atb_i and β

The applied optimization settings for the Vensim optimize function are presented in Table 7.

Calibration type	Policy
Payoff Variable	R2 overall [maximize; weight 1]
Timing	Final
Optimizer	Powell
Random Type	Default
Maximum Simulations	1000
Optimization parameters	AT base[single-family house] AT base[multi-family house] AT base[industry] beta
Model Settings: Initial Time	2009
Model Settings: Final Time	2016 (Swiss cases: BKW, Frutigen, Wohlen, Ostermundigen) 2015 (Bavaria)

Table 4: Optimization settings

The payoff variable «R2 overall» was implemented into the model structure, determining the R^2 of the historical data of the number of prosumers in each consumer group and the simulated data. For details on the operationalization of «R2 overall» is refer to the delivered supporting material.

To avoid optimization results origin from local optima, which are not realistic an iterative approach as applied. Constraints were set to reach values for atb_i between 0 and 50; and for β between 0 and 20. I assumed that adjustment times longer than 50 years are not realistic. Furthermore, a β of more than 20 leads to overly extreme switches of the logit function, which are not considered a realistic representation of investor decision making either. In case optimization results appear that showed values for the optimization parameter exactly the same as the constraints values, then the constraints were narrowed until "free" values were received. Afterwards the results were used as initial values for a last optimization run with the original constraints to retrieve the desired optima in the realistic sphere. Initial values and results are presented in Table 8.

	BKW	Frutigen	Wohlen	Ostermundigen	Bavaria
Initial values					
AT base[single-family house]	3.10951	1	6.41983	15.7564	1
AT base[multi-family house]	4.96525	1	11.5474	48.1234	1
AT base[industry]	1.06982	1	2.21999	4.2768	1
beta	3.3988	1	6.0042	13.0528	-- [1]
Optimization results					
AT base[single-family house]	3.26246	2.85874	5.977	15.7564	0.967126
AT base[multi-family house]	5.43202	0.912162	11.5645	48.1234	1.05663
AT base[industry]	0.939081	1.85872	2.46112	4.2768	0.954974
beta	**4.74309**	**6.20507**	**6.02995**	**13.0528**	**-- [1]**

Table 5: Optimization initial values and results

Appendix E. Scenario Settings

The settings described in Table 9 were used to run the scenario. Command files are provided with the supporting material.

	Base run	Only prosumers	Net metering	Flat rate	Capacity tariff	Capacity tariff with grid friendly behavior
SWITCH net metering 0: net purchase and sale 1: net metering with yearly billing period	0	0	1	0	0	0

[1] In the case of Bavaria no stable optima where found in the sphere defined as realistic, when the beta was part of the optimization. Therefore, the beta value was set fixed to the assumed value of 5.

Switch PV Reimbursement 0: No investment grant 1: Investment grant	1	1	0	1	1	1
SWITCH storage prosumers off	0	1	0	0	0	0
Tariff design[1]	Volumetric	Volumetric	Volumetric	Flat rate	Capacity tariff	Capacity tariff
SWITCH grid optimized behavior off	1	1	1	1	1	0

Table 6: Scenario settings for all presented scenarios

Appendix F. Scenarios "100% economic investors" and "no increase in grid costs"

Raising overall grid costs are the major driver for the increase in the volumetric grid tariff, and not as one would perhaps expect the distribution effect. The scenario "no increase in grid costs" demonstrates that generally increasing grid costs are a major reason for the diffusion of the storage prosumer concept. The (Swiss Federal Office of Energy, 2013) estimates a growth of grid costs in the range of 3-10% annually. The costs growth is explained by the grid expansions investments, partly also caused by the integration of decentral energies, but also through coming smart meter roll-outs In the model, I assume a 3% annual growth. Particularly the storage prosumer concept finds less adopters among single-family houses and commercial customers with constant grid costs. For multi-family houses the storage prosumer concept is already attractive without a strong increase in the grid tariff (Figure 11).

In the scenario "100% economic investors" I switched off the investments of green investors motivated by non-financial factors. In Figure 11 we can see that the diffusion of PV is considerable slower without green investors. It is particularly evident in the case of single-family houses, where a large gap between the base case emerges at prosumers and storage prosumers remain near zero until 2025 and cannot catch up to the level of the base case until the end of simulation. Similar patterns occur for the multi-family houses, although not as extreme as in the case of single-family houses as the profitability has already reached higher levels. For commercial customers nearly no changes are visible as commercial customers are assumed to be deciding only based on economic criteria. The small difference occurs through interaction effect between the other consumer groups. The scenario with only economic investors leads to the conclusion that investors with decision criteria ranging beyond the financial criteria and include factors such as desire for self-sufficiency and technology interest as well as peer effects, are the early adopters for prosumer and storage prosumer concepts and contribute essentially to the market development. Therefore, it is very relevant to consider empirical insights on the motivational factors of the investment decision, to capture a realistic picture of the diffusion.

[1] The tariff designs are activated through the model variables «share XX tariff».

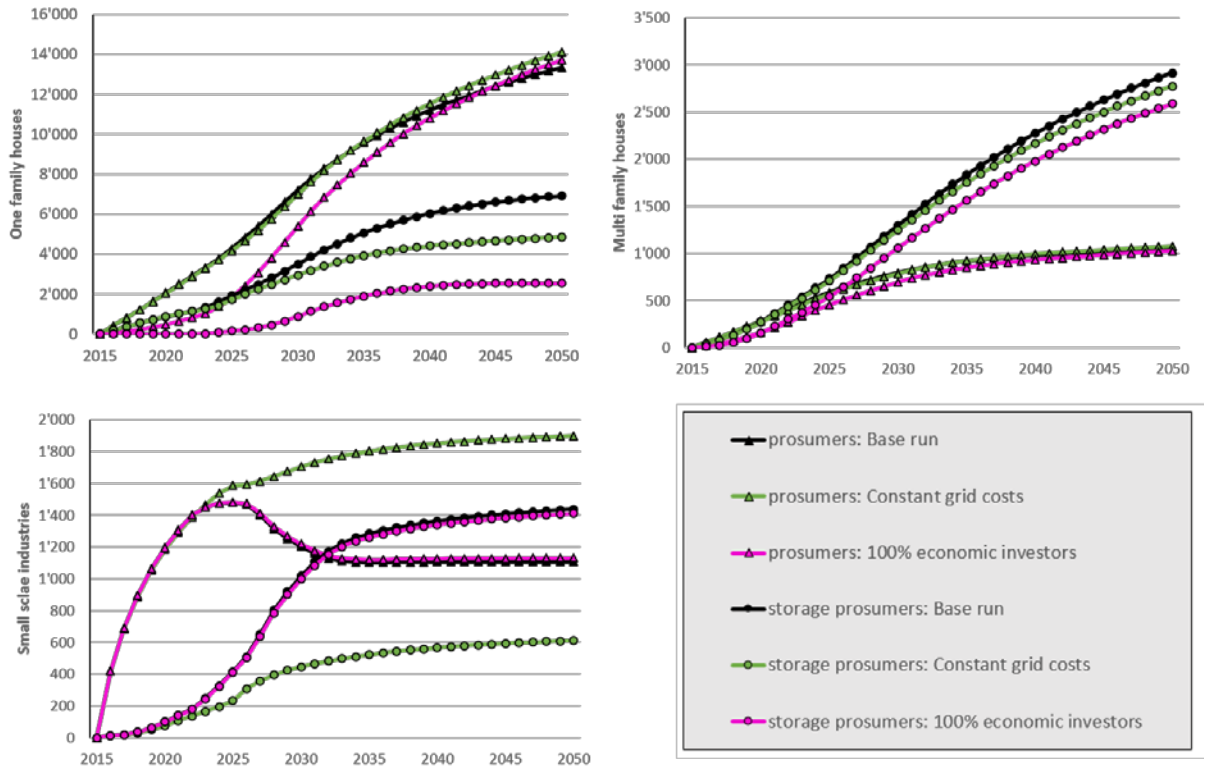

Figure 1: Diffusion of self-consumption concepts under the base run and constant grid cost and 100% economic investors scenario