Evangelos Panos:: Energy Economics Group:: Paul Scherrer Institut

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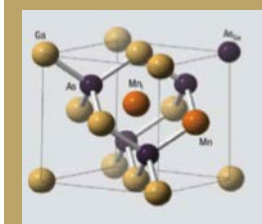
Modelling the long-term solar PV penetration in single- and two- family houses in Switzerland

Energy Systems Modelling and Optimisation Workshop, 26-28.10.2017, Prague

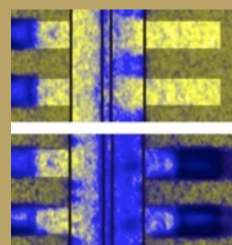
* This presentation is based on Mrs Margelou Master Thesis at PSI and EPFL

The Mission of PSI

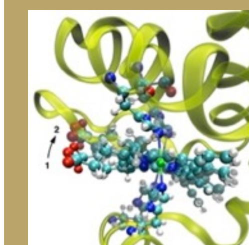
Matter and materials



Energy and environment



Human health



Development
Construction
Operation

Large research facilities

Swiss and foreign users
from academia and industry

more that 2300 external users/year (38 beamports)

Knowledge & expertise

Education

Technology transfer

Researchers in the Energy Economics Group (EEG)

Tom Kober

Group leader

- Energy systems analysis
- CCS
- Low-carbon development

Ramachandran Kannan

Senior Scientist

- Energy systems analysis Switzerland and Europe
- Mobility

Evangelos Panos

Senior Scientist

- Energy systems analysis Switzerland / Europe /global
- Power systems analysis
- Electricity markets
- Low-carbon development
- Integrated modelling assessment

Martin Densing

Senior Scientist

- Energy markets
- Power sector

Antriksh Singh

PostDoc Fellow

- Electricity system analysis Switzerland / Europe

Hassan Aymane

PhD Student

- Storage solutions

Julia Granacher

Master Student

- New energy pathways in the industrial sector

1 open PhD position

- Scenario and modelling

Selected recent/on-going projects of Energy Economics Group in PSI

Swiss-focussed projects

- **Swiss Competence Centre for Energy Research (SCCER)**: Efficient Technologies and Systems for Mobility & Supply of Electricity
- **Energy Systems Integration Platform**: Long term energy scenario analysis with chemical storage option
- **Electricity Markets**: Electricity market designs and oligopolistic capacity expansion and market-bidding (BEM)
- **ISCHESS**: Integration of stochastic renew-ables in the Swiss electricity supply system
- **IDEAS4Cities:** Model-based analysis of rural and urban energy systems

International projects

- **World Energy Council**: WEC Global Scenario Study and regional deep-dives
- **Insight_E**: EEG and TAG member of an inter-disciplinary energy think tank supporting the European Commission
- **Eurpean electricity market modelling** considering dispatch aspects and network constraints
- **AMPERE**: Assessment of Climate Change Mitigation Pathways
- **Burden sharing** of climate change mitigation efforts
- **Local Atmospheric Pollution:** synergies and co-benefits of climate change mitigation

Main areas in energy-economic modeling at PSI Energy Economics Group

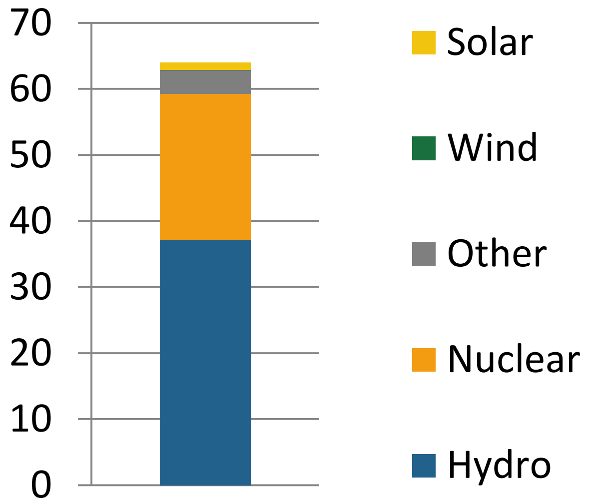
	System-cost minimization (perfect competition)	Profit maximization (imperfect competition – game theoretic)		Utility maximization
	Energy system models	**Energy market models**	**Single utility models**	**Integrated assessment models**
local	City energy system (TIMES)		**Hydropower** ∿ (stochastic & risk)	
CH	Swiss energy system (TIMES)	**BEM** ∿ Bi-level electricity market (Mixed Complementarity)		
EU	EU electricity system ∿ (TIMES)			
World	**GMM** (global multi-regional MARKAL)			**MERGE-ETL** (energy, economy, climate)

∿ : electricity sector model

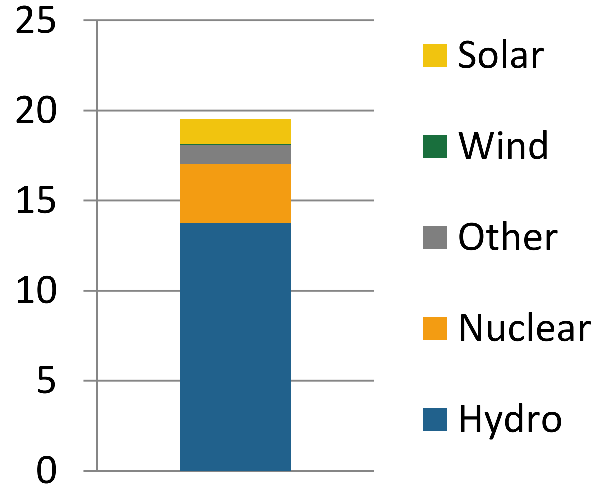
All models are written in GAMS

Overview of the Swiss Energy System, 2015

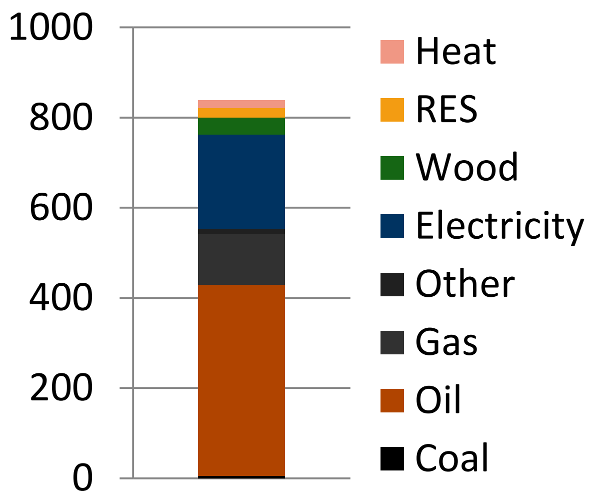
ELECTRICITY GENERATION (TWh)



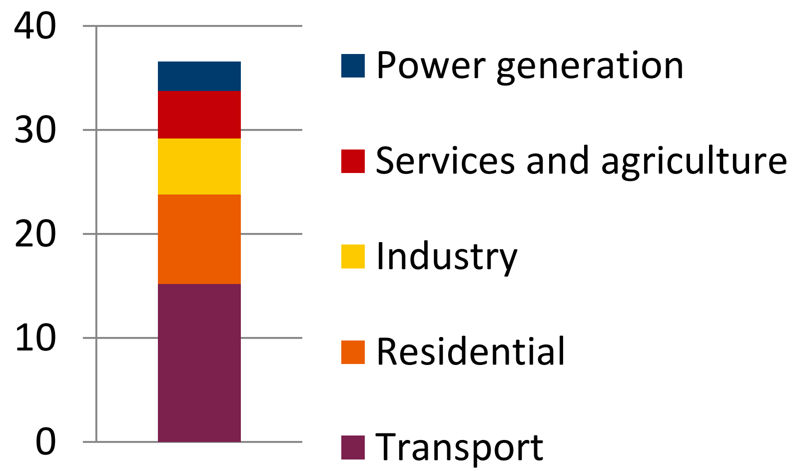
ELECTRICITY CAPACITY (GW)



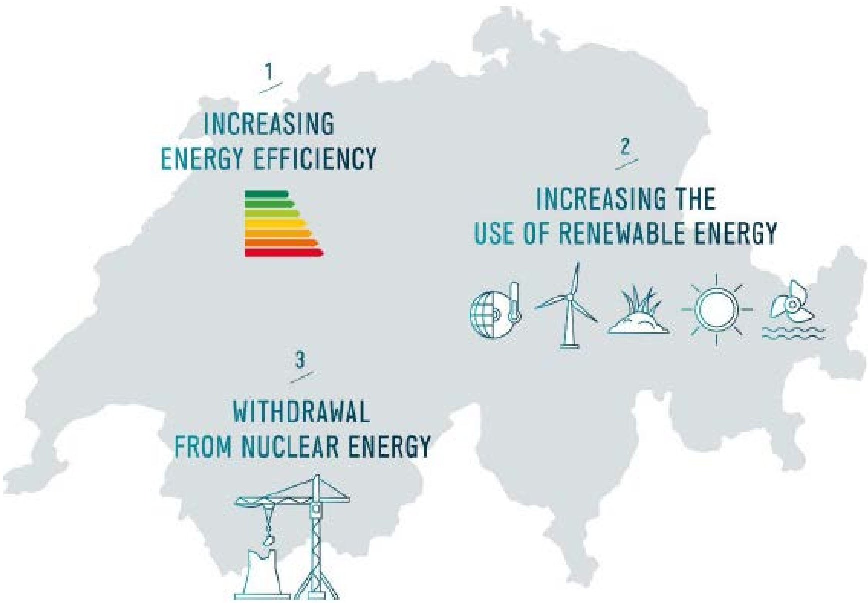
FINAL ENERGY CONSUMPTION (PJ)



ENERGY RELATED CO2 EMISSIONS (Mt)



New energy act: three strategic objectives



Measures to increase energy efficiency
- Buildings
- Mobility
- Industry
- Appliances

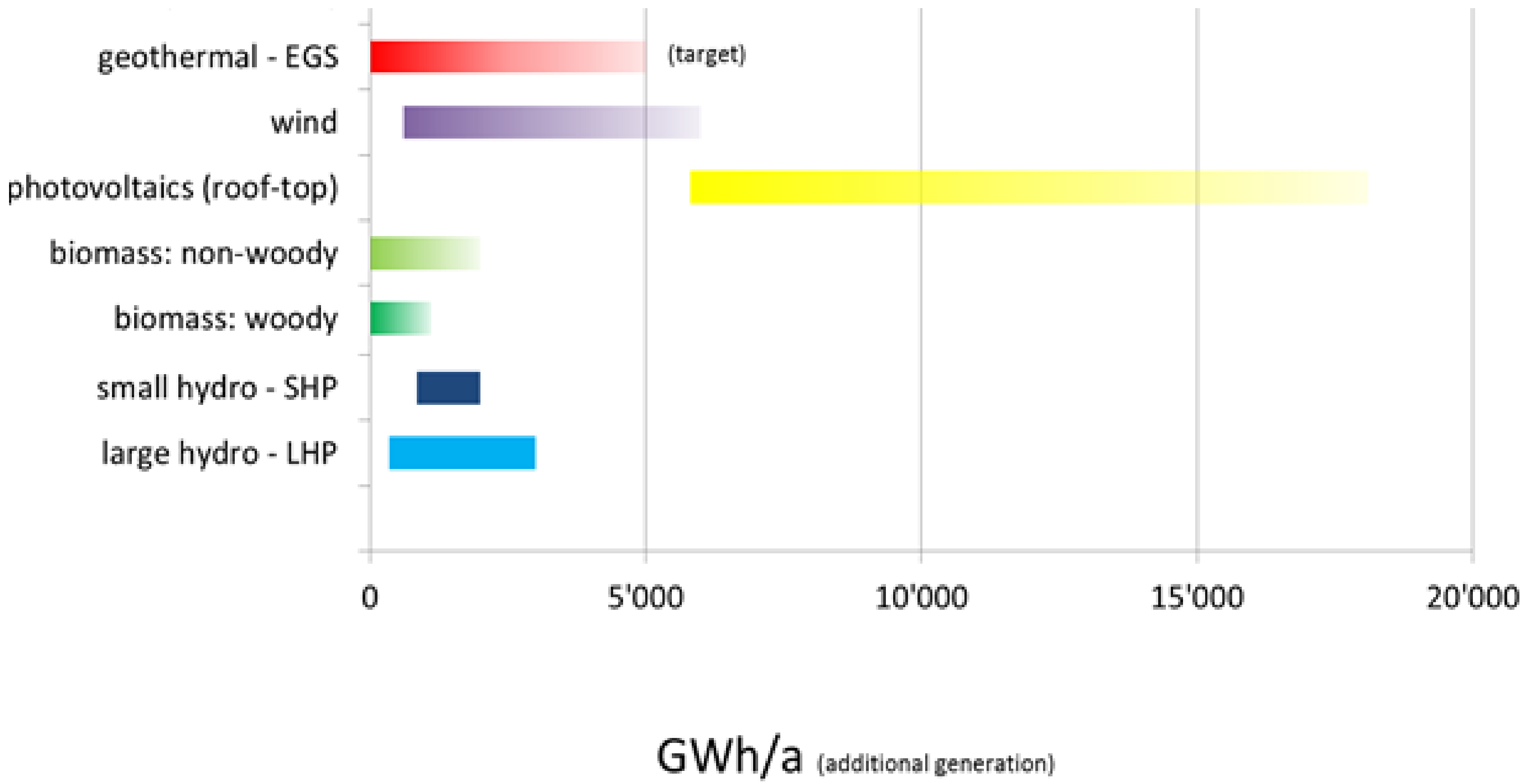
Measures to increase the use of renewable energy
- Promotion
- Improvement of legal framework

Withdrawal from nuclear energy
- No new general licenses
- Step-by-step withdrawal – safety as sole criterion

Source: Swiss Federal Office for Energy

Potential in Switzerland for electricity generation from renewables, additional to 2015

- Roof-top solar PV is the main source of non-hydro based renewable electricity generation in Switzerland, with a contribution that could reach 19 TWh/yr.

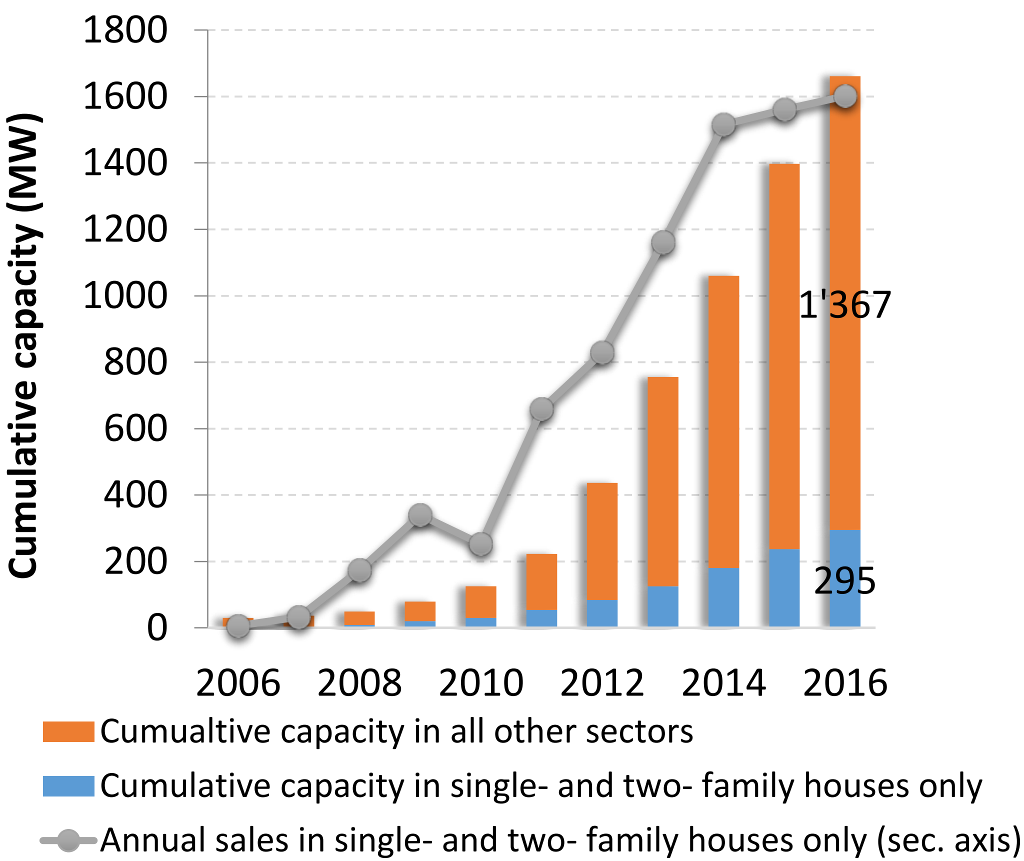


Source: Hirschberg et al., (2017) Potentials, costs and environmental assessment of electricity generation technologies

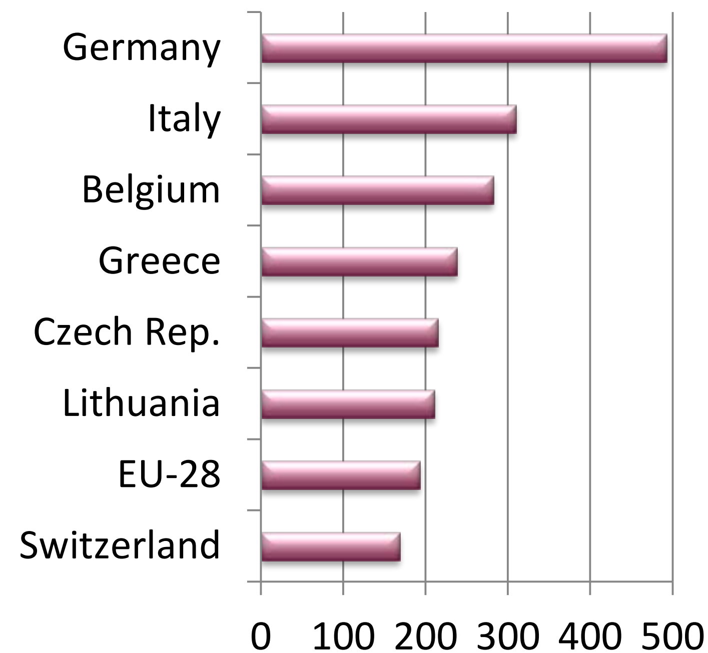
Penetration of solar PV in Switzerland

- The solar PV market continuous to grow, but there is a deceleration over the last 3 years in the small-scale applications in single- and two- family houses

INSTALLED CAPACITY OF SOLAR PV 2006 - 2016



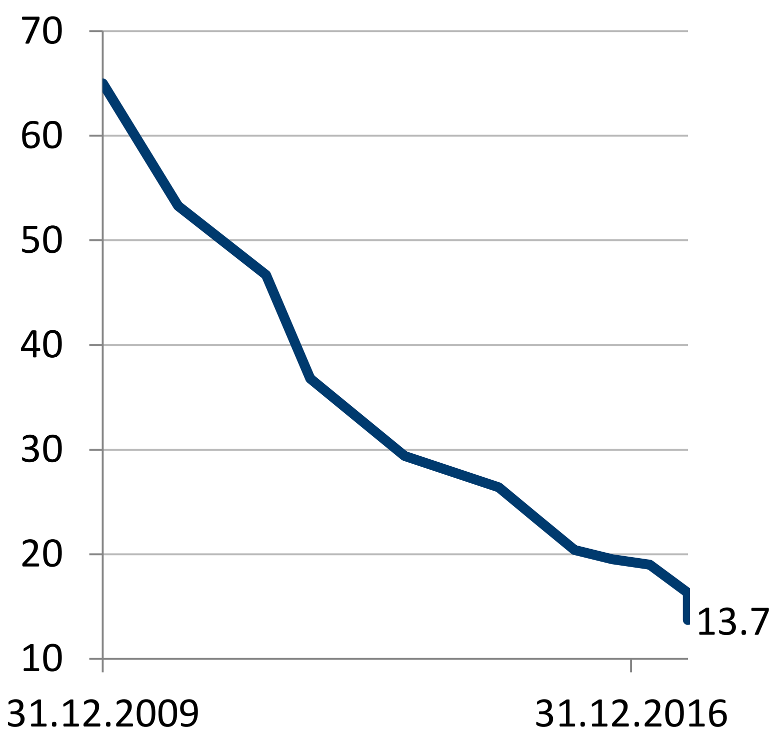
SOLAR PV MW/MILLION CAPITA 2015



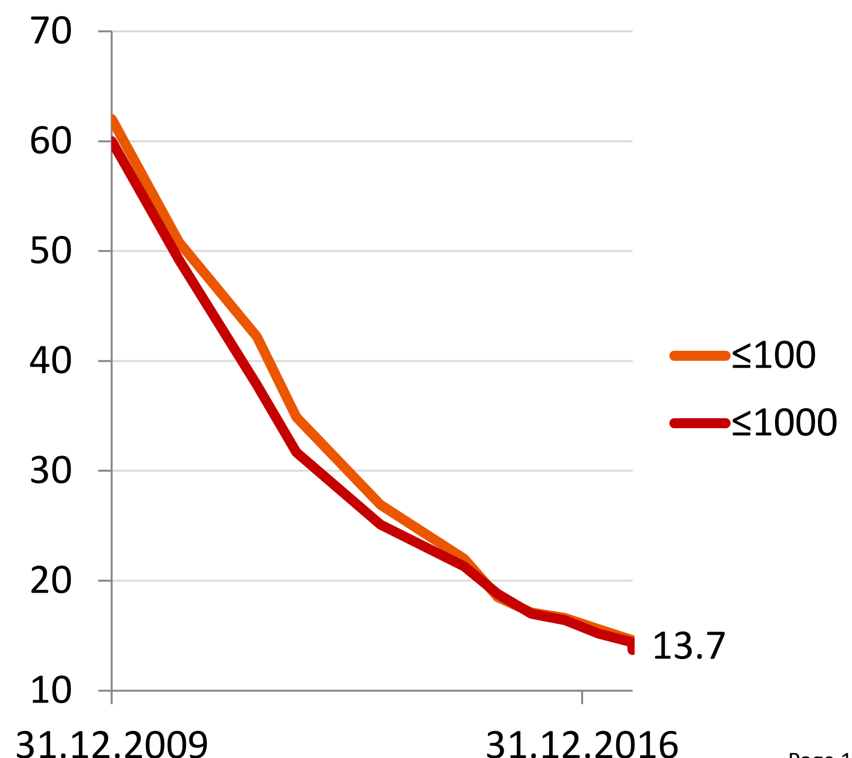
Policy supports in solar PV are fading out

- < 2 kW , no support
- [2, 10] kW , compensation up to 30% in the investment cost
- (10, 30] kW, feed-in tariff or compensation up to 30% in the investment cost
- > 30 kW , feed-in tariff
- Electricity price today ranges from 5.7 – 47.2 Rp./kWh (average 17.7 Rp./kWh)

FEED-IN TARIFF FOR ≤30 KW (Rp./kWh)

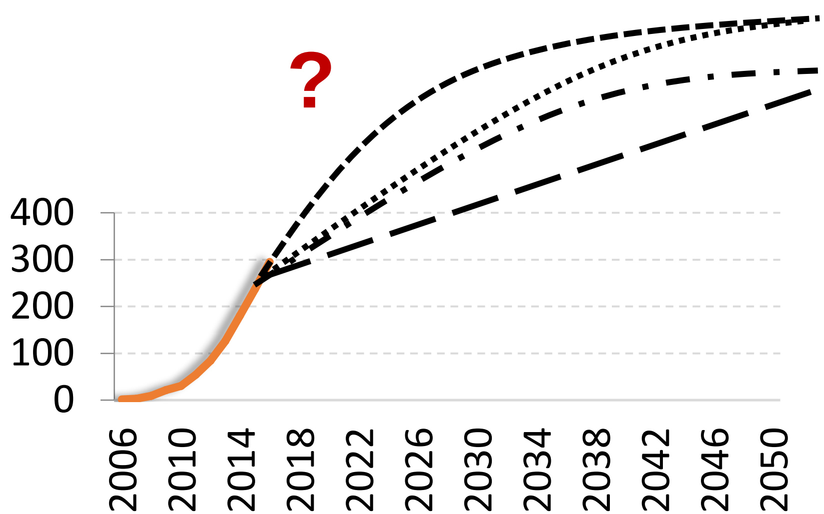


FEED-IN TARIFF FOR >30 KW (Rp./kWh)



Motivation of this work – research questions

- The deceleration of solar PV in single- and two- family houses observed in the last years, does it indicate an immature market relying on policy supports?
- Will this market grow further in Switzerland, or the solar PV installations would be mainly be at industrial, commercial and multi-family buildings?
- Which are the main factors influencing the decision of individuals to install a solar PV system in their roof:
  - Economic profitability of the investment?
  - Environmental sensitivity?
  - Budgeting constraints and financing of the investment ?
  - Influence from friends and neighborhood (mimetics)?



Additional questions

- How will the diffusion process evolve until 2050?
- What are the key drivers affecting the timing of the investment in solar PV?
- Is the time period sufficient for the diffusion process to reach a saturation point?

Methodology – building an Agent Based Model

Agent: A single- or two- family house located at a canton

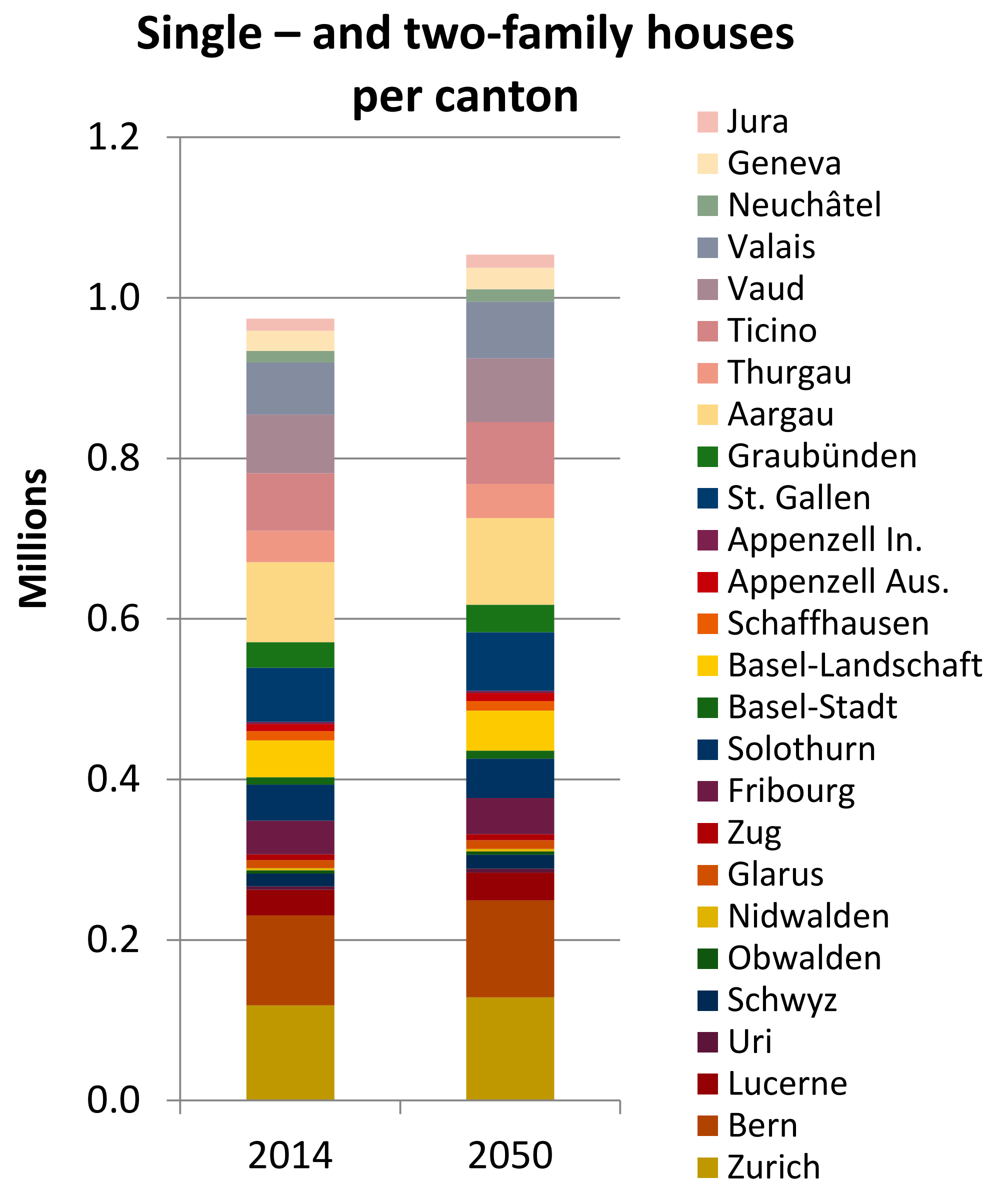
It is characterised by the following attributes:

- Income (average of the adults in the house)
- Age and education level (average of the adults in the house)
- Socio-economic status , life values, social network (links with other agents)
- Annual electricity consumption
- Expected annual electricity production from 1kW solar PV
- Usable roof-top area to install solar PV

Based on Palmer et al. (2015). Modelling the difussion of residential PV in Italy ; and on Robinson et al. (2013). GIS-integrated ABM of residential PV difussion

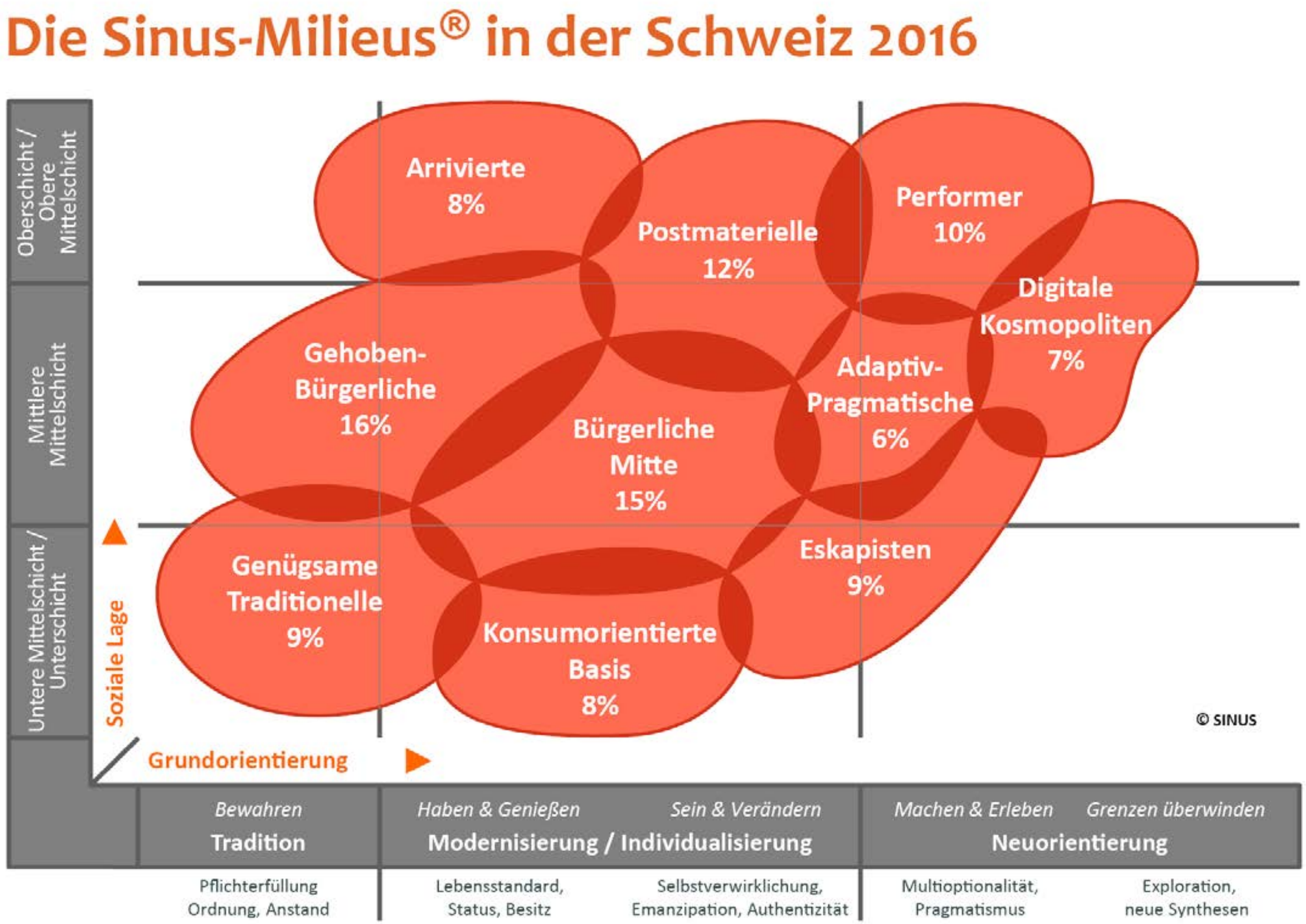
Creating the agents: setting their total number

- The total number of single- and two- family houses is dynamic over time
- The number of agents in each Swiss canton is pre-defined, based on the assumption of the number of households in the Swiss Energy Strategy Scenarios (Prognos, 2012)
- The location of an agent defines also the expected annual production from 1kW solar PV, based on the solar irradiation in this location



Creating the agents: social structure

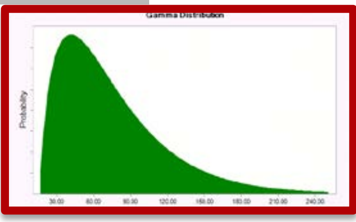
- We use the segmentation of the population that is provided by the Sinus-Milieus® institute
  – It is an accurate description of people sensitivities, orientations, life values and goals
  – It is used in social sciences, media and business agencies



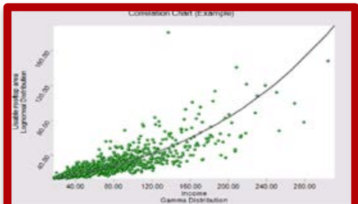
Creating the agents: Initialisation of attributes

Creation of a synthetic population of agents

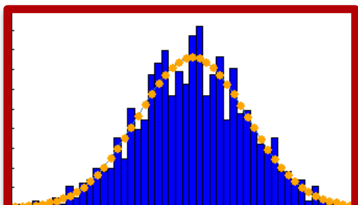
- The initialisation of each agent in each canton is based on Monte Carlo sampling, using fitted distributions to statistics provided by the Swiss administrative registers



1. We fit probability distributions to statistics of income, age, and rooftop area, annual electricity consumption; we fit also on Sinus-Milieus® . This is done per canton



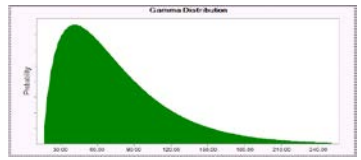
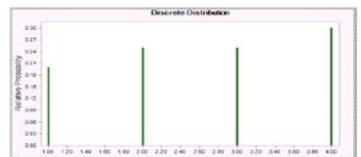
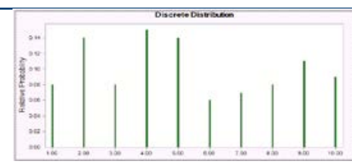
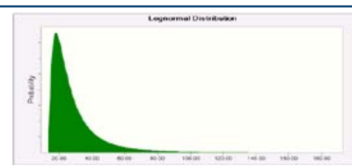
2. We establish correlations between the distributions of step 1, e.g. income-age, income-rooftop area, income-Sinus; this is done per canton



3. We apply Monte Carlo sampling in the joint probability distributions of step 2, to initialise the income, age, rooftop area, annual electricity consumption and Sinus category of each agent in each canton

4. Based on the Sinus-Milieus® category from step 3, the links with other agents are created for each agent in each canton

Creating the agents: distributions of the random variables for Monte Carlo sampling

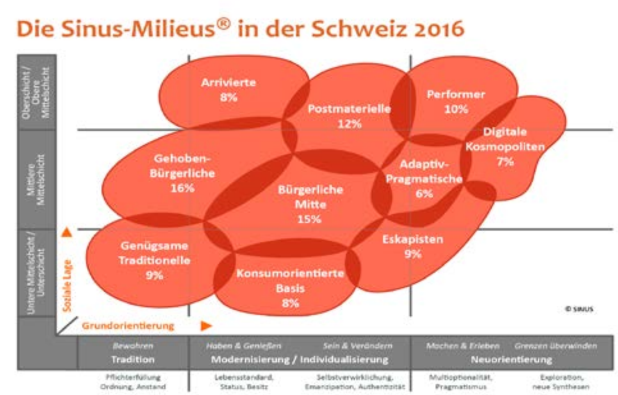
Random variable	Probability distribution		Adjustment in 2017-2050
Income	Gamma		The mean is shifted by 0.6% p.a.
Age	Discrete		Ages 20-39 decrease by 0.33% p.a. ; Ages 40-65 increase by 0.67% p.a.
Sinus-Mileus® category	Discrete		Adjusted following past trends
Annual electricity consumption	Gamma		The mean is shifted by 0.1% p.a.
Rooftop area	Log-normal		Remains unchanged over time, but the area needed for 1 kWp Solar PV is gradually reduced from 7.2 m^2 to 4 m^2

Correlations: Income-Age 89% , Income-Sinus 88%, Income-rooftop 85%

Creating the agents: social network

- Each agent can have links with another agents
  - The number of links depends on Sinus-Milieus® category
- There are different probabilities for an agent to establish a link with other agents belonging to different Sinus-Milieus® category (see table below)
- There is a 60% probability to establish link with an agent in the same location
- There is 0.25-1% probability that an agent breaks a link and reconnects with another agent in the next year

An agent connects with another agent of:	Probability
the same Sinus-Milieus® category	70 – 85%
adjacent Sinus-Milieus® category	35 – 42%
a category with distance 2	5 – 10%
a more distant category	0%



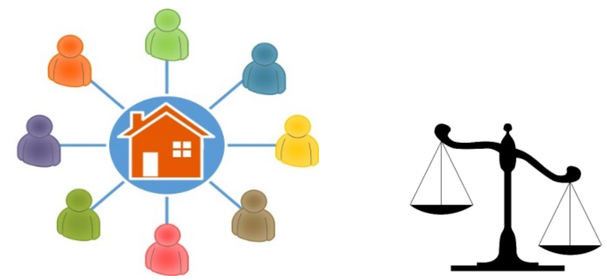
Based on Palmer et al. (2015). Modelling the difussion of residential PV in Italy ; and on Robinson et al. (2013). GIS-integrated ABM of residential PV difussion

Modelling the decision of an agent

Economic partial utility

Environmental partial utility

Income partial utility



Communication partial utility

Total utility

$$U_{total}(i) = u_{ec}(i) \cdot w_{ec}(i) + u_{en}(i) \cdot w_{en}(i) + u_{in}(i) \cdot w_{in}(i) + u_{com}(i) \cdot w_{com}(i)$$

0 Threshold 1

Specification of the partial utilities

Economic partial utility

Discounted payback period of the investment, based on:

- agent's electricity consumption,
- agent's location,
- electricity prices,
- governmental financial incentives,
- choice of the support scheme
- CAPEX and OPEX of the investment
- Degradation rate of solar PV panel
- Expected electricity production from PV

Income partial utility

Household's income, based on:

- agent’s location,
- agent's education level
- agent's age

Agent

A single- or two- family house in Switzerland

Environmental partial utility

Amount of CO_2 emissions saved, based on:

- total electricity production from all installed solar PV panels in Switzerland over their lifetime

Communication partial utility

Number of links to other adopters, based on:

- agent's location
- agent's Sinus-Milieus® category

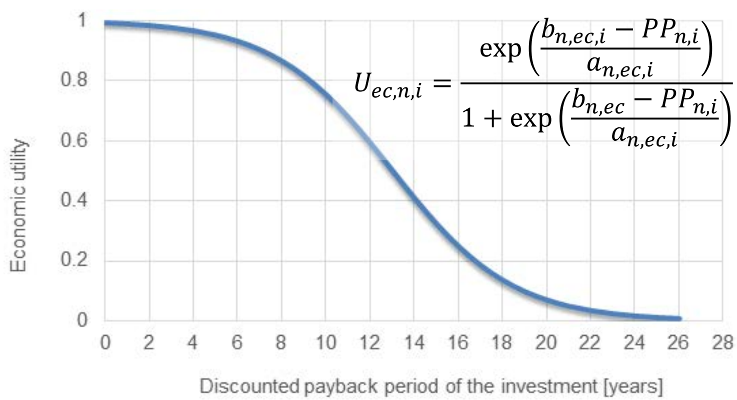
Based on Palmer et al. (2015). Modelling the difussion of residential PV in Italy

Partial utilities are sigmoid functions

The general functional form of the utility function in each year n and for each agent i is:

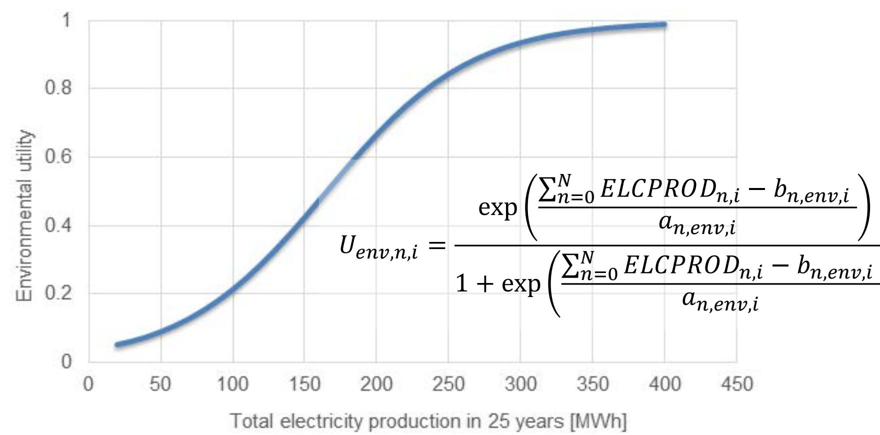
$$U(x)_{n,i} = \frac{\exp\left(\frac{b_{n,i} - x_{n,i}}{a_{n,i}}\right)}{1 + \exp\left(\frac{b_{n,i} - x_{n,i}}{a_{n,i}}\right)}$$

where x is the explanatory variable, b is the tipping-point parameter and a is the shape parameter



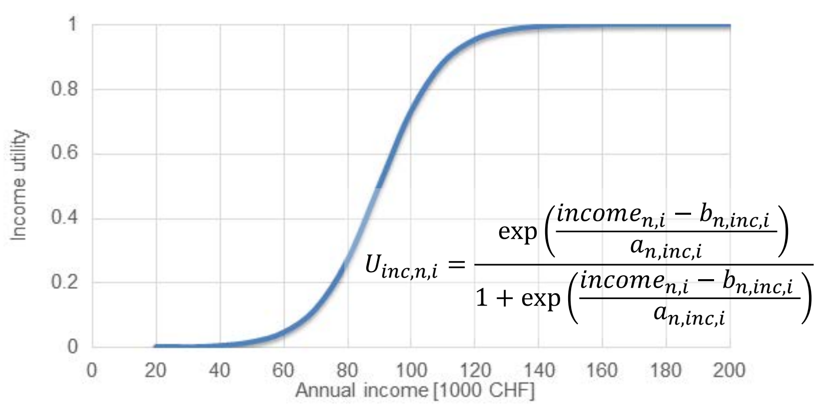
$$U_{ec,n,i} = \frac{\exp\left(\frac{b_{n,ec,i} - PP_{n,i}}{a_{n,ec,i}}\right)}{1 + \exp\left(\frac{b_{n,ec} - PP_{n,i}}{a_{n,ec,i}}\right)}$$

Economic partial utility



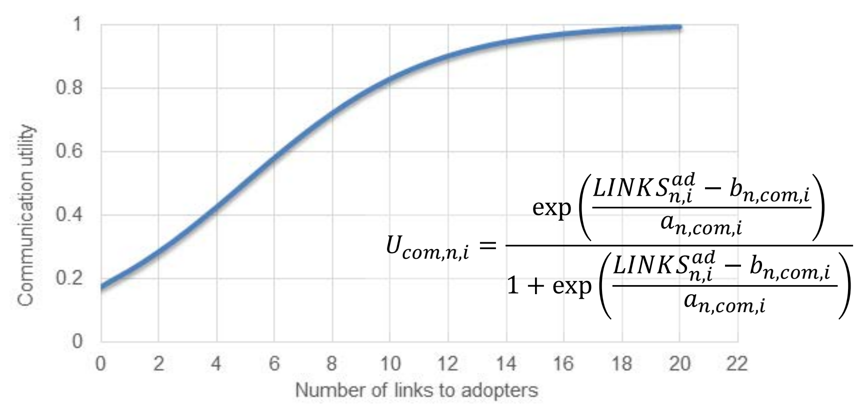
$$U_{env,n,i} = \frac{\exp\left(\frac{\sum_{n=0}^{N} ELCPROD_{n,i} - b_{n,env,i}}{a_{n,env,i}}\right)}{1 + \exp\left(\frac{\sum_{n=0}^{N} ELCPROD_{n,i} - b_{n,env,i}}{a_{n,env,i}}\right)}$$

Environmental partial utility



$$U_{inc,n,i} = \frac{\exp\left(\frac{income_{n,i} - b_{n,inc,i}}{a_{n,inc,i}}\right)}{1 + \exp\left(\frac{income_{n,i} - b_{n,inc,i}}{a_{n,inc,i}}\right)}$$

Income partial utility

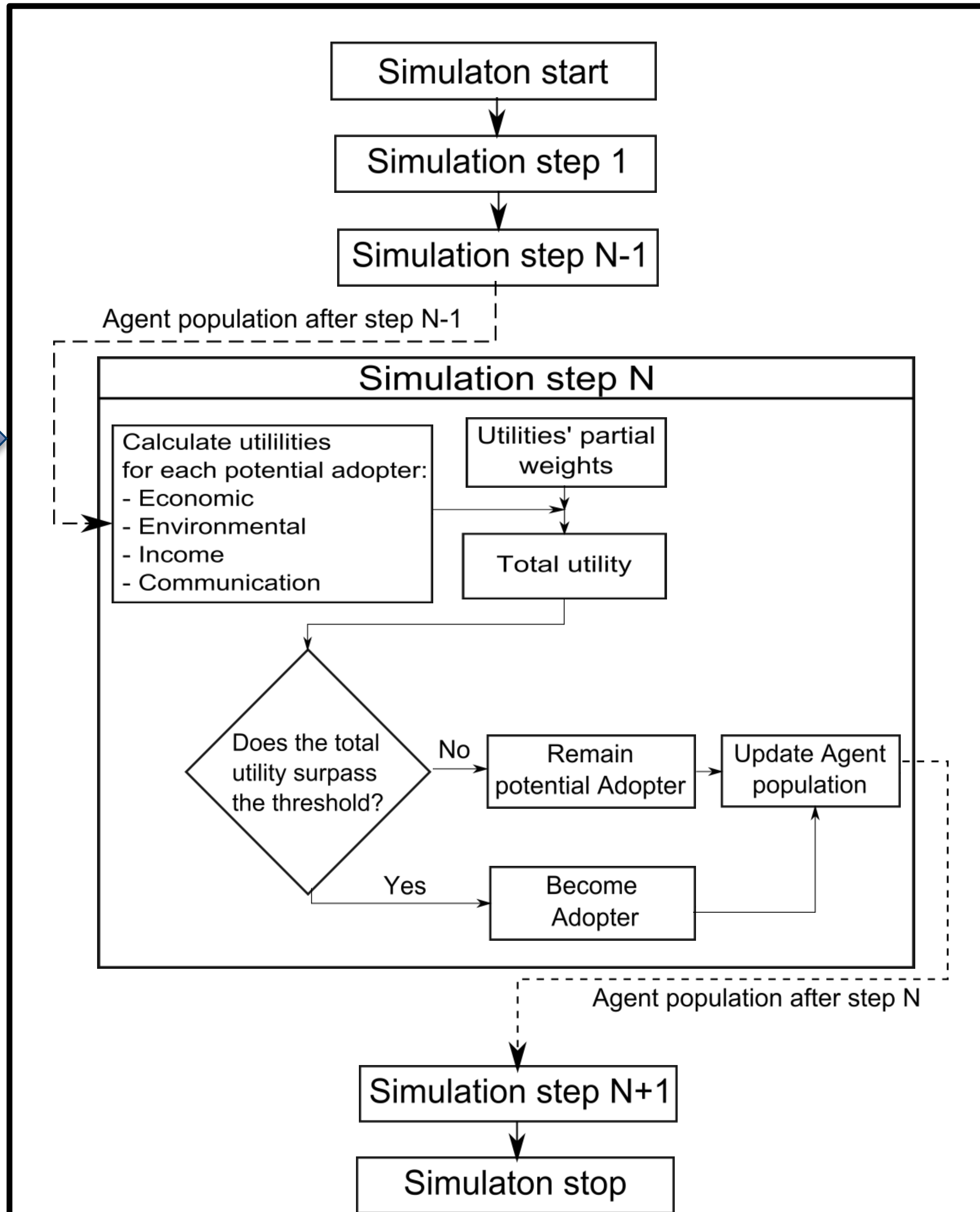


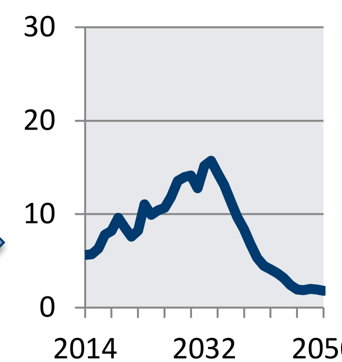
$$U_{com,n,i} = \frac{\exp\left(\frac{LINKS_{n,i}^{ad} - b_{n,com,i}}{a_{n,com,i}}\right)}{1 + \exp\left(\frac{LINKS_{n,i}^{ad} - b_{n,com,i}}{a_{n,com,i}}\right)}$$

Communication partial utility

Modelling framework

Creation of the agent population via Monte Carlo sampling





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Model calibration and validation

- We split the model parameters into two vectors:
  - vector $\boldsymbol{\lambda}$ contains the weights of the utilities and the decision threshold
  - vector $\boldsymbol{\theta}$ contains the tipping and shape parameters of each utility

- We initialise $k = 1 \ldots K$ different instances of vectors $\boldsymbol{\theta}_k$, such that the obtained utilities have «much» different shapes

- For each $\boldsymbol{\theta}_k$ we estimate vectors $\boldsymbol{\lambda}_k$, via maximum likelihood, to minimise the calibration error (= rate of adoption and cumulative capacity)

- We evaluate each model $(\boldsymbol{\theta}_k, \boldsymbol{\lambda}_k)$ against the statistics 2014-2015

- We choose this model k that has the minimum validation error

2009 – 2015: data on sales and capacity

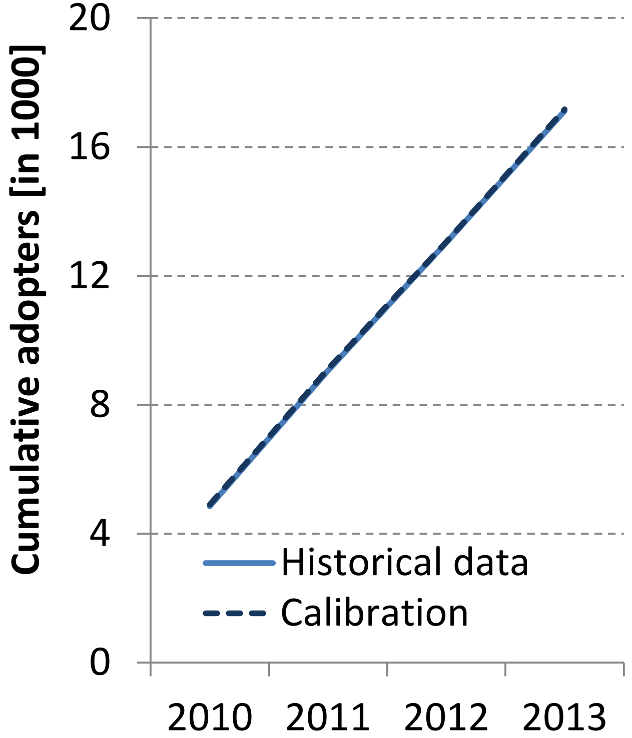
2009 – 2013
calibration period

2014 – 2015
validation period

Calibration and validation error

- The calibration matches the cumulative sales (adopters) of solar PV in single- and two- family houses in Switzerland and the cumulative installed capacity
- The obtained validation errors in cumulative sales and capacity are 1-3%

MODEL CALIBRATION OF ADOPTERS



MODEL VALIDATION ERRORS OF KEY VARIABLES IN 2015

	Actual data 2015	Model Result	Relative Error
Number of installations	6300	5711	**-9.35%**
Installed capacity (MW)	56	55	**-2.43%**
Cumulative installations	28557	28230	**-1.15%**
Cumulative capacity (MW)	237	230	**-3.11%**

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Long-term scenarios assessed with the model

Reference scenario

- Most likely development of investment costs and electricity prices
- Default discount rates of 5.5%

Sensitivity on policy support schemes

- Rapid phase out from 2018, versus continuation until 2040

Sensitivity on electricity prices

- ± 10% deviation in the electricity price of reference

Sensitivity on cost of capital (discount rate)

- Higher discount rate of 12.5%

Sensitivity on solar PV learning rates

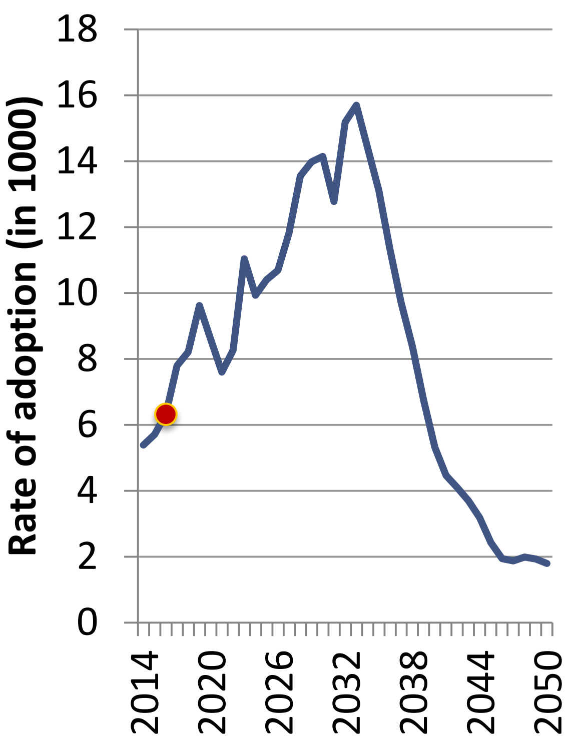
- ± 20% deviation in the investment cost of Reference

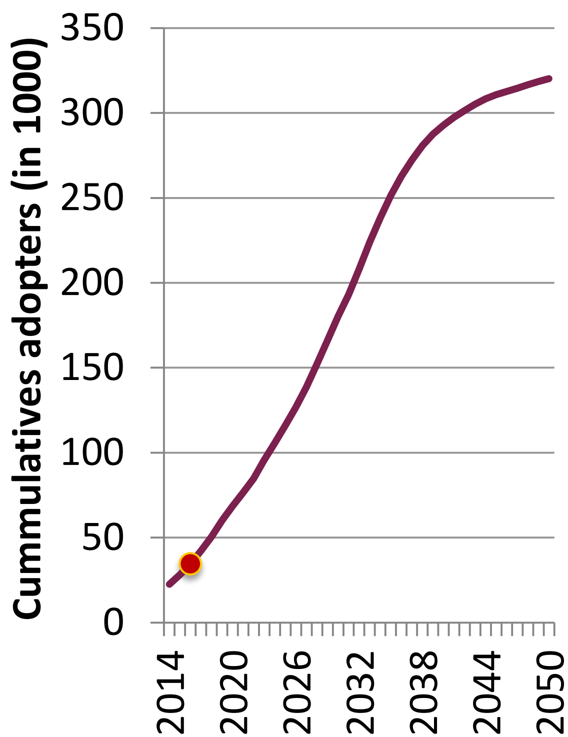
Reference scenario: Assumptions and results

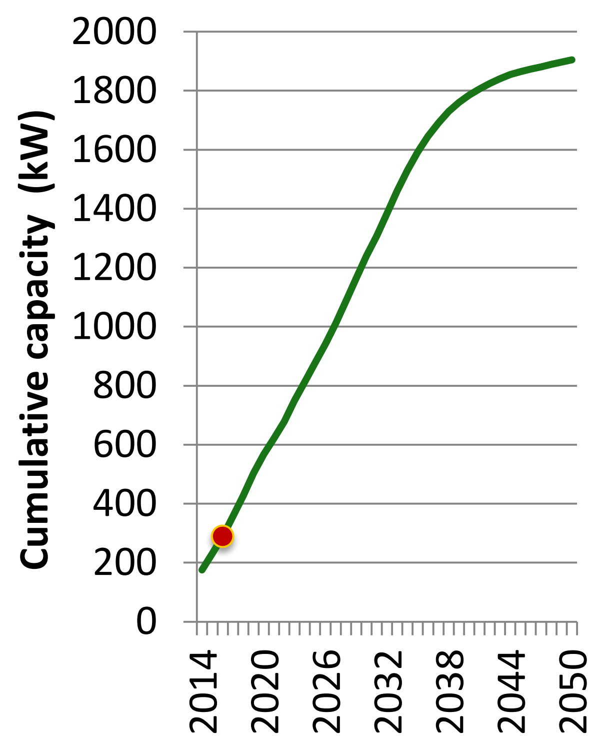
Assumptions

- Discount rate 5.5%
- Exponential phase out of financial incentives by 2030
- Specific investment costs from 2500 – 4600 CHF/kW in 2015 to 920 – 1580 kW in 2050, for systems from 2 kW to 20 kW
- Electricity prices from 17 Rp./KWh in 2015 to 30 Rp./kWh in 2050 (on average)

Results



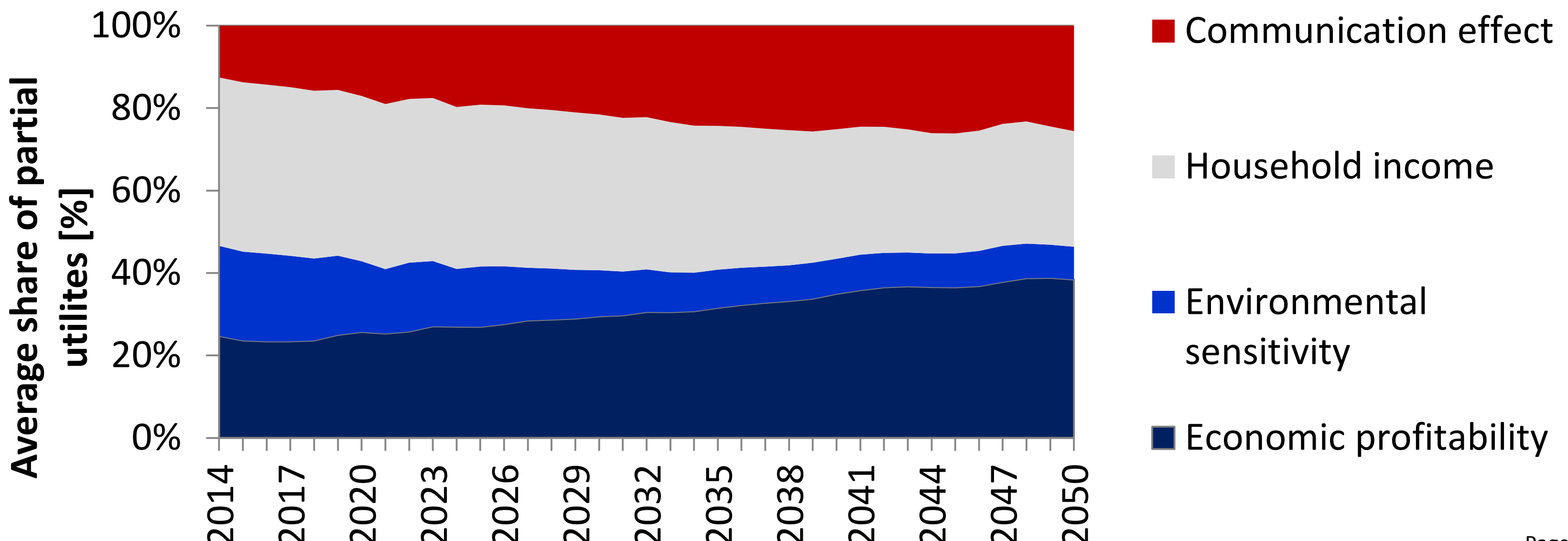




Reference scenario: Factors influencing the investment decision

- High weights of income and economic utilities before 2030 → diffusion is driven by high income classes and financial incentives
- After 2030, the weight of income utility reduces as middle-class becomes an adopter
  - But they install smaller systems and this negatively impacts the environmental utility
- Towards the end of the projection period, the diffusion process is driven by the profitability and communication utilities

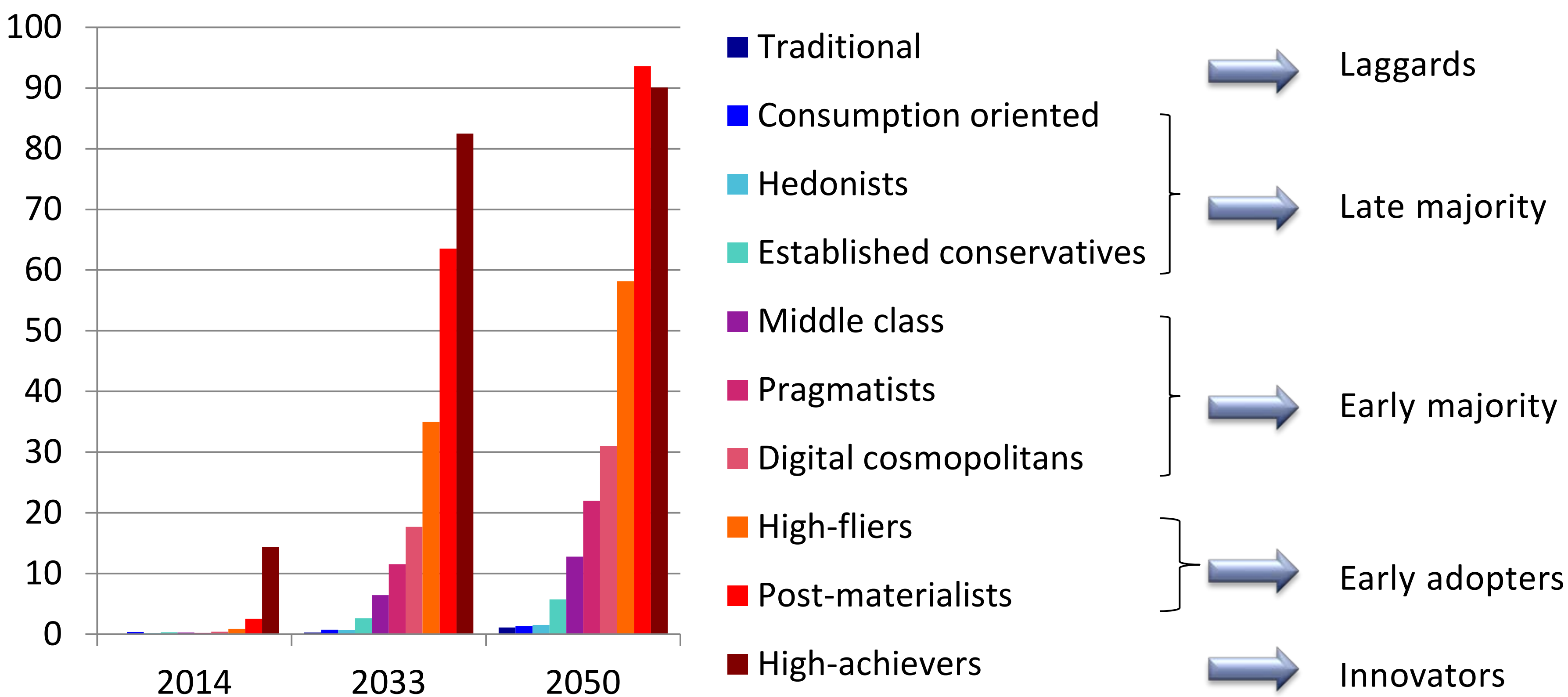
AVERAGE SHARE OF PARTIAL UTILITIES IN TOTAL UTILITY ACROSS ALL ADOPTERS



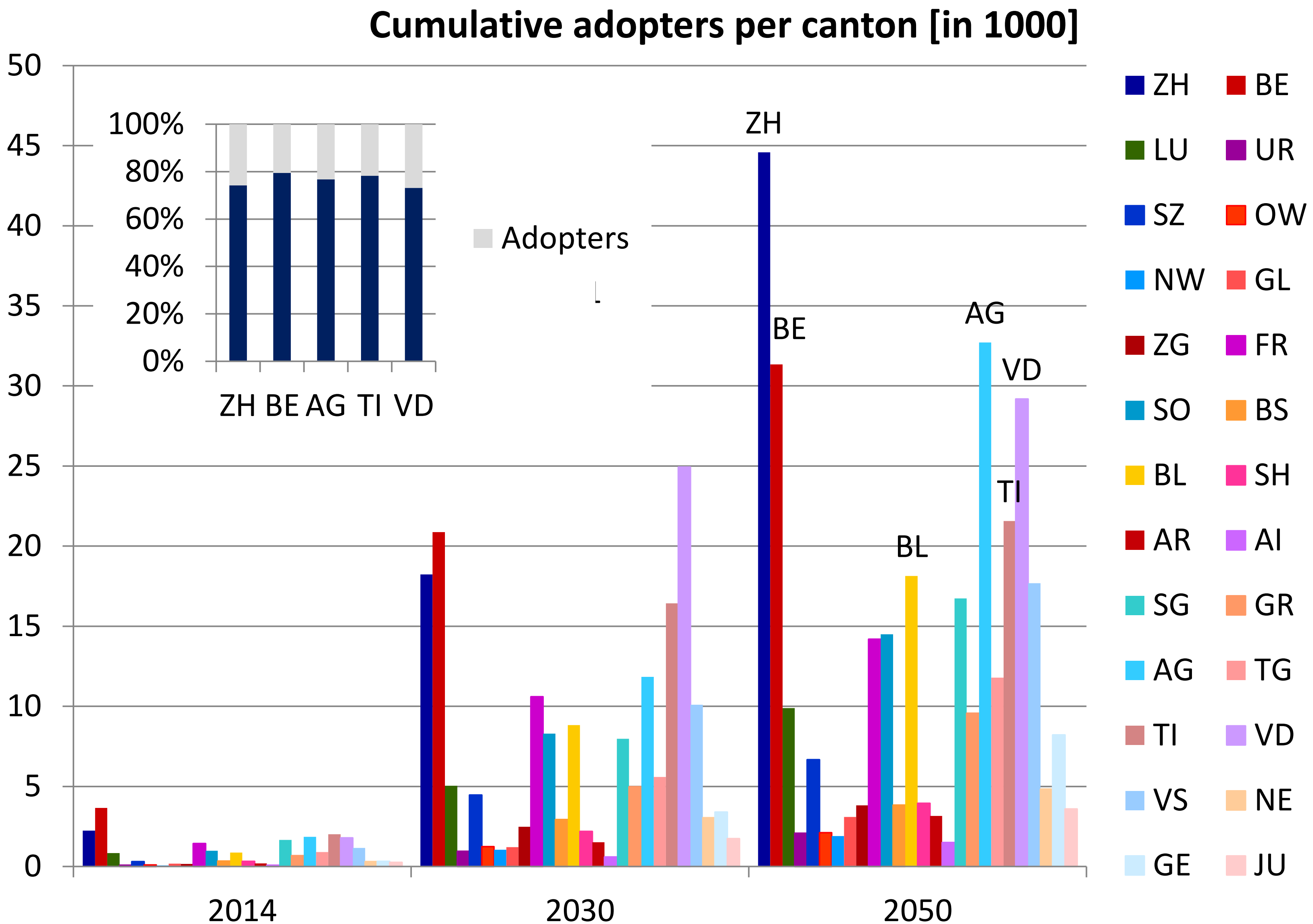
Reference scenario: Adopters by Sinus-Milieus® category

- By 2030 the pool of innovators and early adopters is almost exhausted
- Early majority becomes adopter during the decade 2030 – 2040
- Late majority starts to emerge after 2040
- Laggards do not significantly appear before 2050

ADOPTERS PER SINUS-MILIEUS® CATEGORY IN THOUSANDS

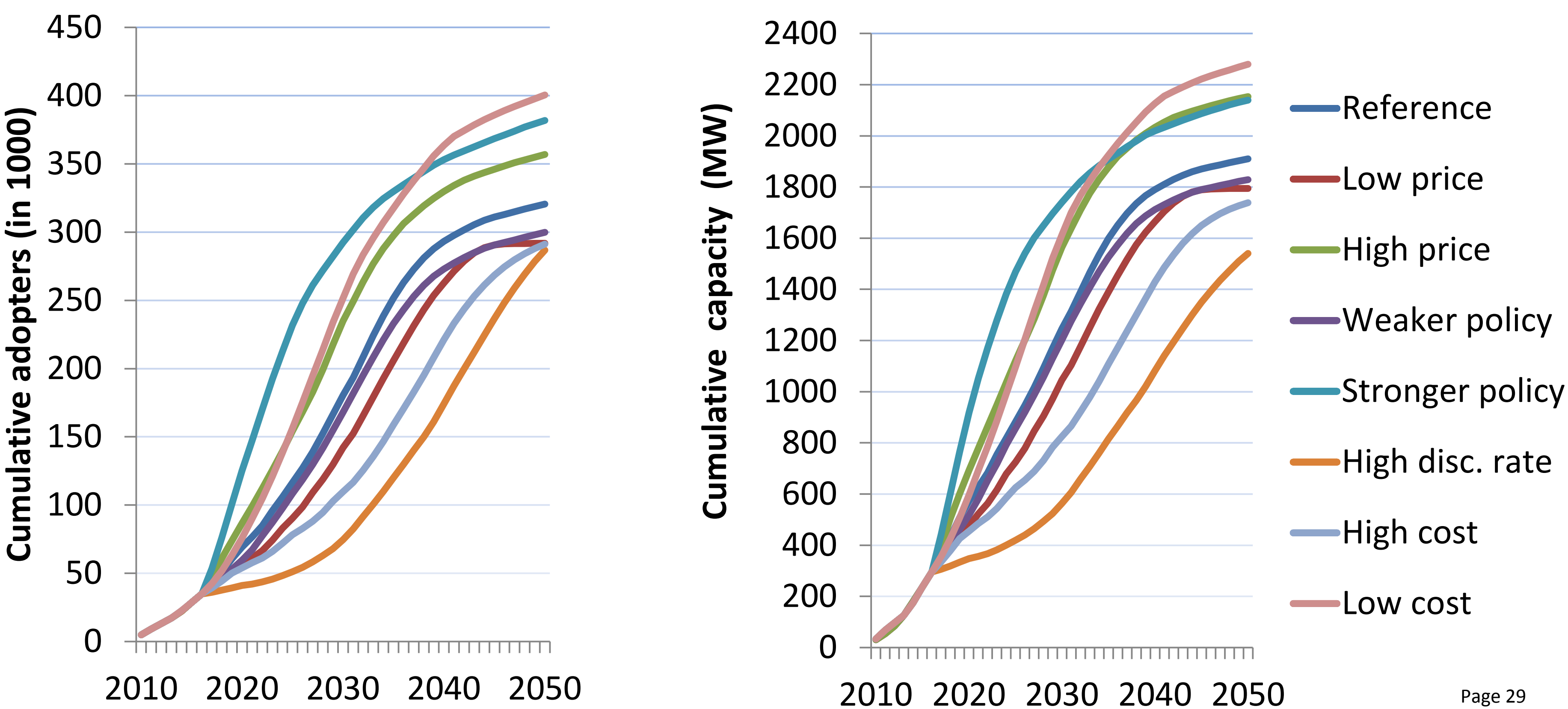


Reference scenario: Adopters by canton

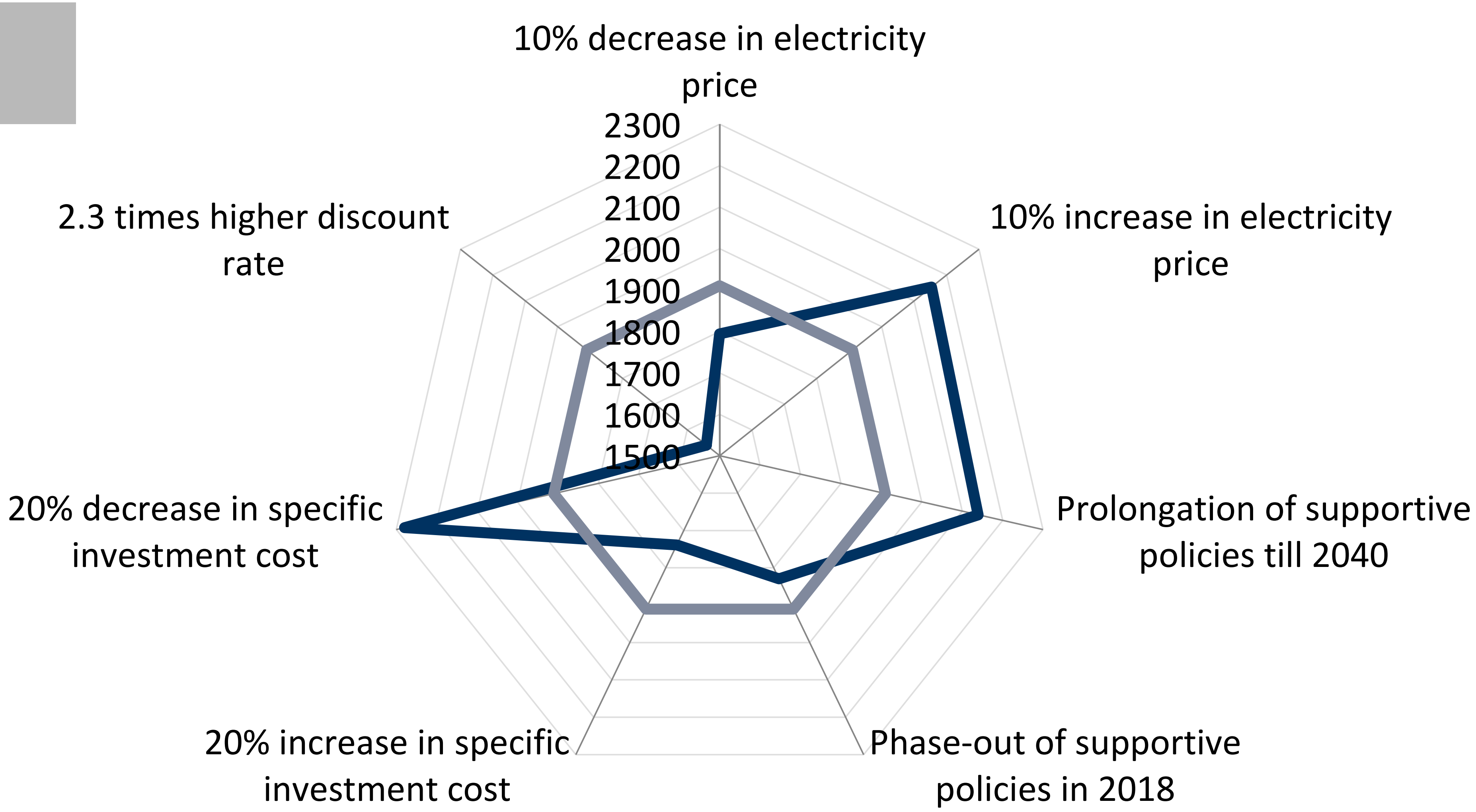


Comparison of scenarios

- Weak financial incentives delay the diffusion process by a decade, while strong financial incentives could bring it forwards by 20 years
- Low specific investment costs bring the decision to invest 15 years earlier, and the saturation point of the diffusion process is not reached by 2050 compared to Reference
- Low electricity prices slowdown the diffusion process by a decade, and the adoption rate falls close to zero by 2050 → the diffusion is not evolving after this year
- High cost of capital prohibits middle-class to become an adopter



Summary of solar PV installed capacity in the different scenarios



Conclusions

- The economic profitability of the investment is the most important decision factor
- A steep reduction in the support schemes slows down the diffusion process, but it does not stop it due to the reduction of the specific investment costs
- Thus it can be argued that the direct government support, although is more costly to tax payers, is a safe option to ensure a faster diffusion of the solar PV in order to meet mid-term targets
- The cost of capital as it is anticipated by individuals significantly affects not only the timing of the investment but also its size at the end of the simulation
- The diffusion process is also sensitive to the electricity prices, with low electricity prices causing a deceleration of the process especially until 2025-30
- The adoption curve displays a tipping point by the time the majority of innovators have been already became adopters
- Key role in increasing or maintaining the adoption rate after this point of time plays the communication component (peer effects); because we do not model the "mass-media" effects, there is a saturation in the increase of direct links with adopters
- All the above imply that the diffusion process of solar PV in single- and two- family houses in Switzerland is starting gaining its momentum, but in the near term (3-5 years from now) is sensitive to the electricity price, support schemes and specific investment cost

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Thank you for your attention

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