POTENTIALS AND LIMITATIONS OF PHOTOVOLTAIC-BASED CELLULAR ENERGY SYSTEMS IN SOUTHERN GERMANY

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Fraunhofer Institute for Systems and Innovation Research ISI

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Agenda

1. Motivation
2. Research Framework and Objectives
3. Methodology
4. Case study
    1. Scenario set-up
    2. Results
5. Findings and Outlook

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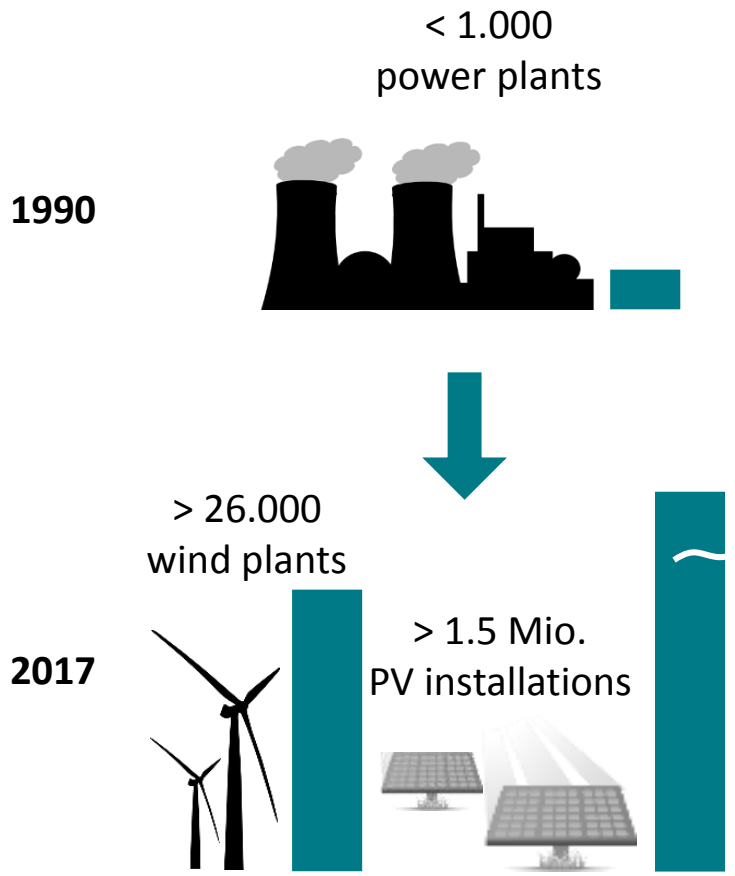
Motivation

- The transformation of the energy system is ongoing:
  - Growth of RES
  - Decentralization of generation
  - Sector coupling and electrification
- Challenges:
  - Volatility of generation
  - Congestions in the transmission and distribution grid
  - Limited dispatchable generation
- Possible solutions:
  - Creating decentralized / distributed energy systems?
  - Promoting higher degrees of autonomy to achieve robustness?



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Research Framework: Cellular energy systems

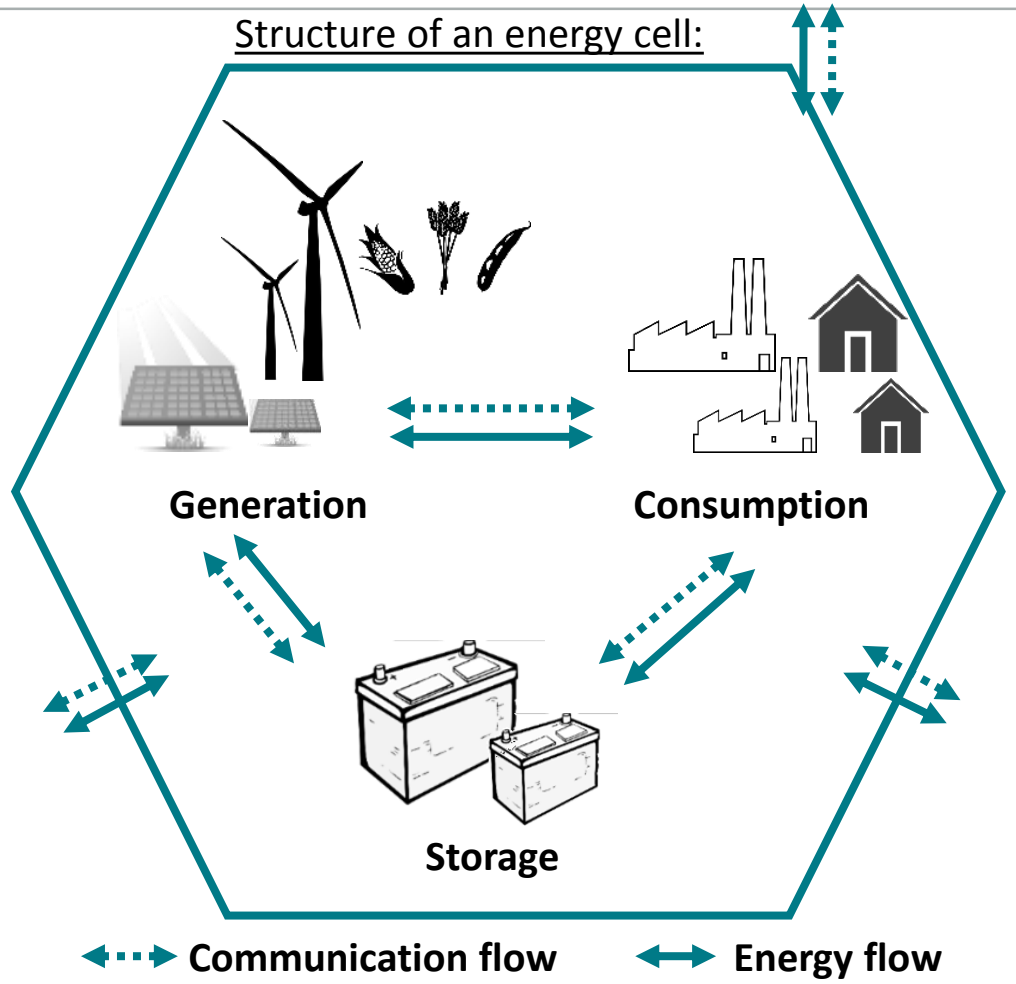
Cellular approach

- Balancing of generation and demand at the most local level before an interaction with a neighboring or superior cell [3, 4].
- Participants are linked both physically and virtually [4]. Standardized interactions
- Energy cells can range from single buildings or devices up to whole (grid) regions [3].

Objectives:

- Integrate RES
- Increase/maintain system security
- Decrease complexity

[2,5]



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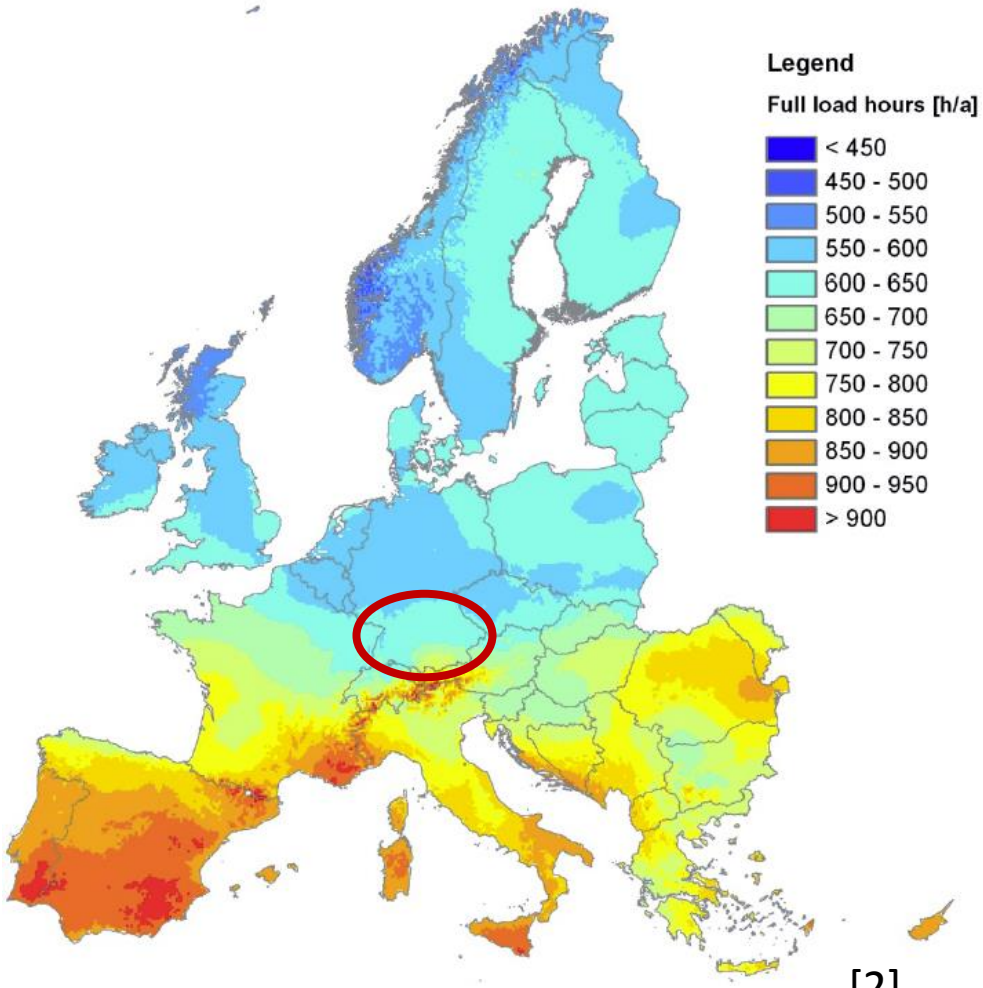
Research Framework: **C/sells**

- **Demonstration of cellular energy systems**
- **Research project in the framework of SINTEG (funding: BMWi)**
- **Volume: 100 Mio. € (Total)**
- **showcase with a reach of approx. 30 Mio. citizens**
- **32 ‘demonstrators’, 9 cells aiming at active participation of citizens**

[1]



[2]

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Research objective

- What is the cost-minimal configuration of PV and battery storage in a region?
- Is the PV potential in a region sufficient for covering a substantial amount of demand?
- Can we observe and identify (un-) wanted effects on a systemic level?

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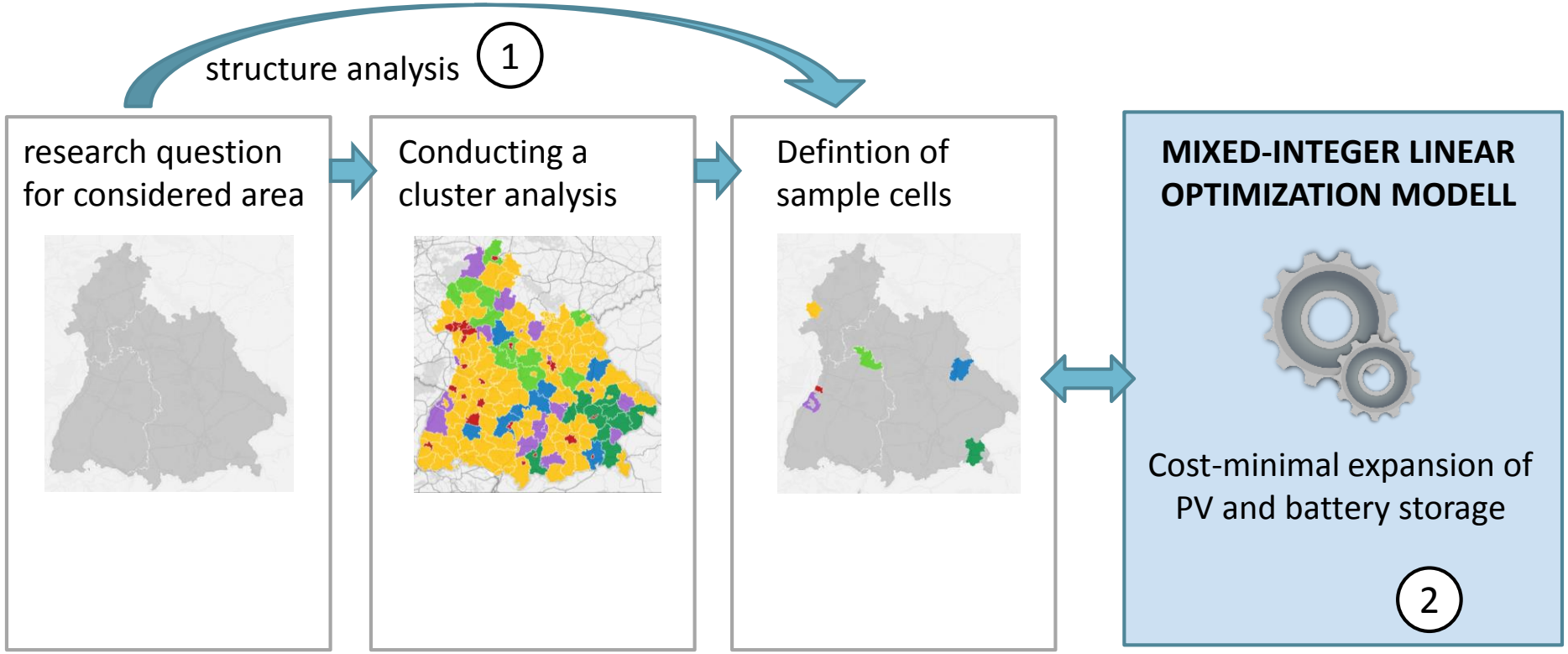
Methodology: Overview



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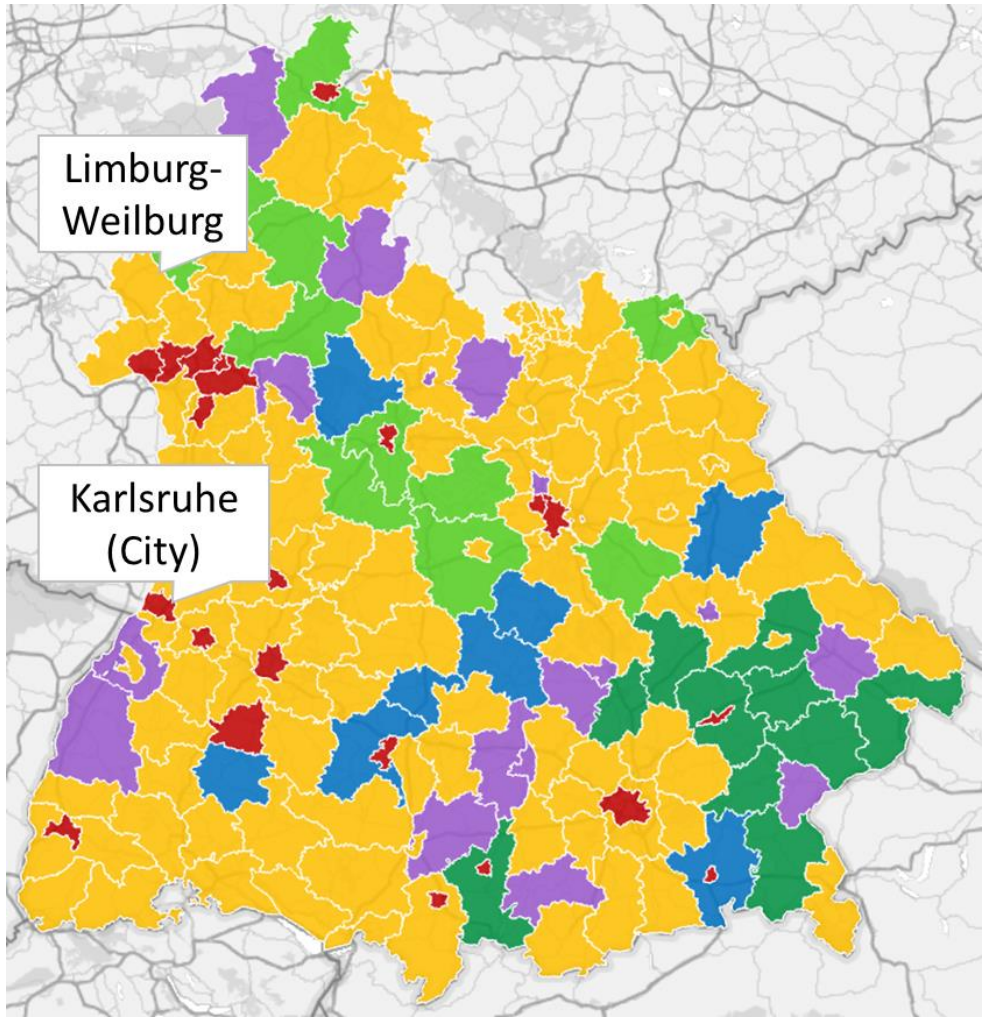
Methodology: Structure analysis: clustering regions and identifying sample cells



- Cluster 1: public sector, service sector, wholesale and retail, urban structure
- Cluster 2: public sector, service sector, wholesale and retail, rural structure
- Cluster 3: High installed capacity of wind turbines, high PV expansion potential, especially roof-top plants
- Cluster 4: high share of nocturnal electricity demand
- Cluster 5: high share of process industry
- Cluster 6: Very high expansion potential for ground-mounted PV

- Agglomerative-hierarchical Ward method
- Parameters: PV potential, wind capacity, population density, share of selected process load

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Methodology: Optimization model (1/3)

General approach:

- Calculation of cost-optimal PV and storage capacity in the context of a cellular energy system for 2030
- Mixed-integer linear optimization model implemented in Python
- Hourly resolution

Target function:

- Minimisation of annual expenditures for electricity within an energy cell

Technological choice and variables:

- Target variables: Installed capacity of PV and battery storage
- Central and aggregated dispatch
- Generation for wind and biomass is given as fix parameters

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Methodology: Optimization model (2/3)

Restrictions:

- Minimum degree of autonomy within a cell
  - Autonomy is defined as an annual balance according to McKenna et al. 2015 [6]

Assumptions:

- Grid
  - No restrictions (temporal or spatial) for the exchange of electricity within a cell or with neighboring/superior cells
  - Grid costs not considered
- Battery storage
  - Only PV-surplus is stored
  - Electricity from storage is not sold outside the cell

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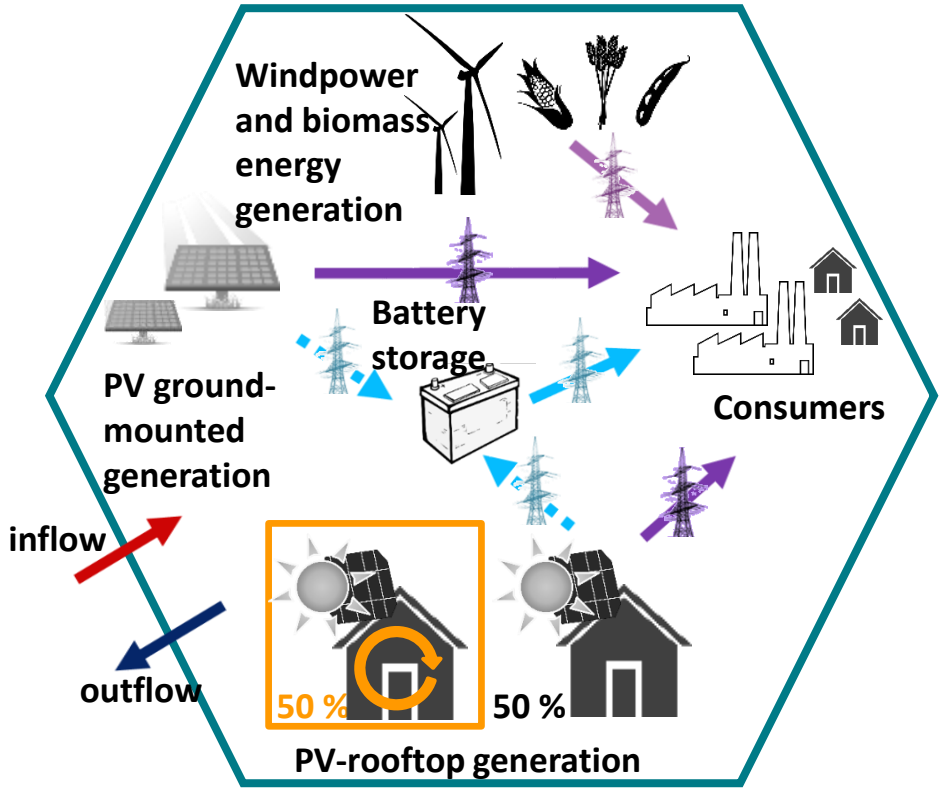
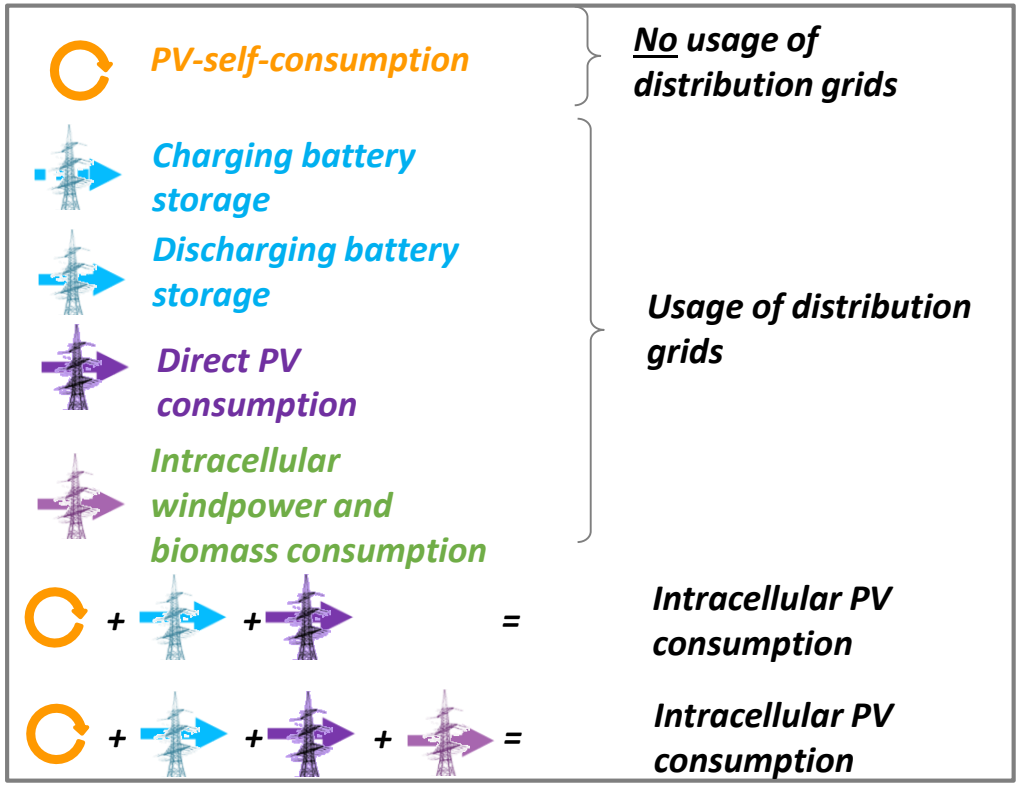
Methodology: Optimization model (3/3): Electricity flows and roles within a cell define the degree of autonomy achieved





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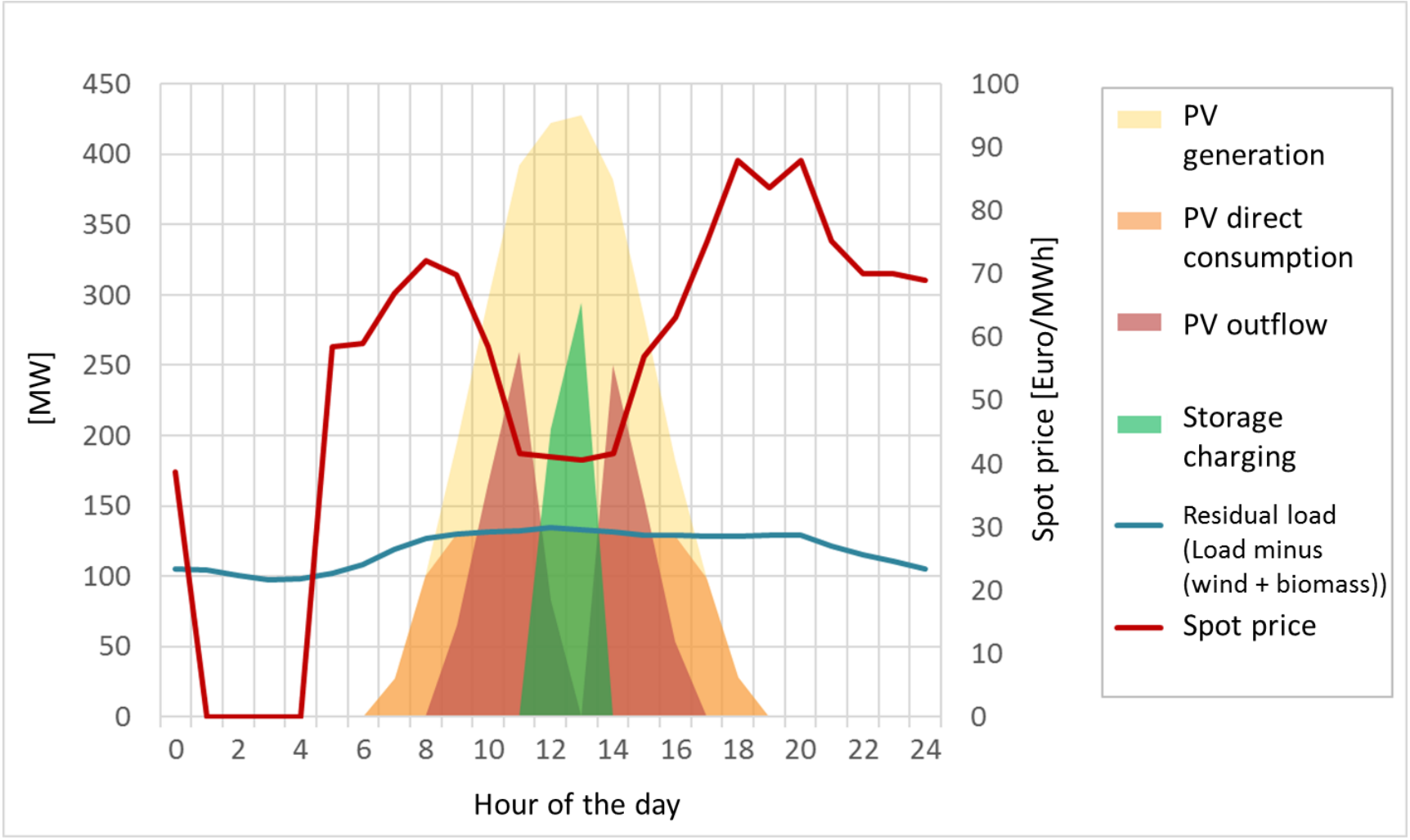
Methodology: How the model works



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Case Study: Case set-up - quantifying a minimal-cost configuration for PV and battery storage

Reference Case

- Not modelled as a cellular approach
- No minimal degree of autonomy
- All taxes as well as grid related surcharges considered
- Arbitrage possible
- 50 % self-consumption on the consumer side of the meter

→ Reference case considering all relevant cash flows

Cellular Case

- Explicit modelling of a cellular approach
- Minimal degree of autonomy of 60 %
- All taxes as well as grid related surcharges considered
- Arbitrage possible
- 50 % self-consumption on the consumer side of the meter

→ Cellular energy system with a regulatory framework based on current conditions

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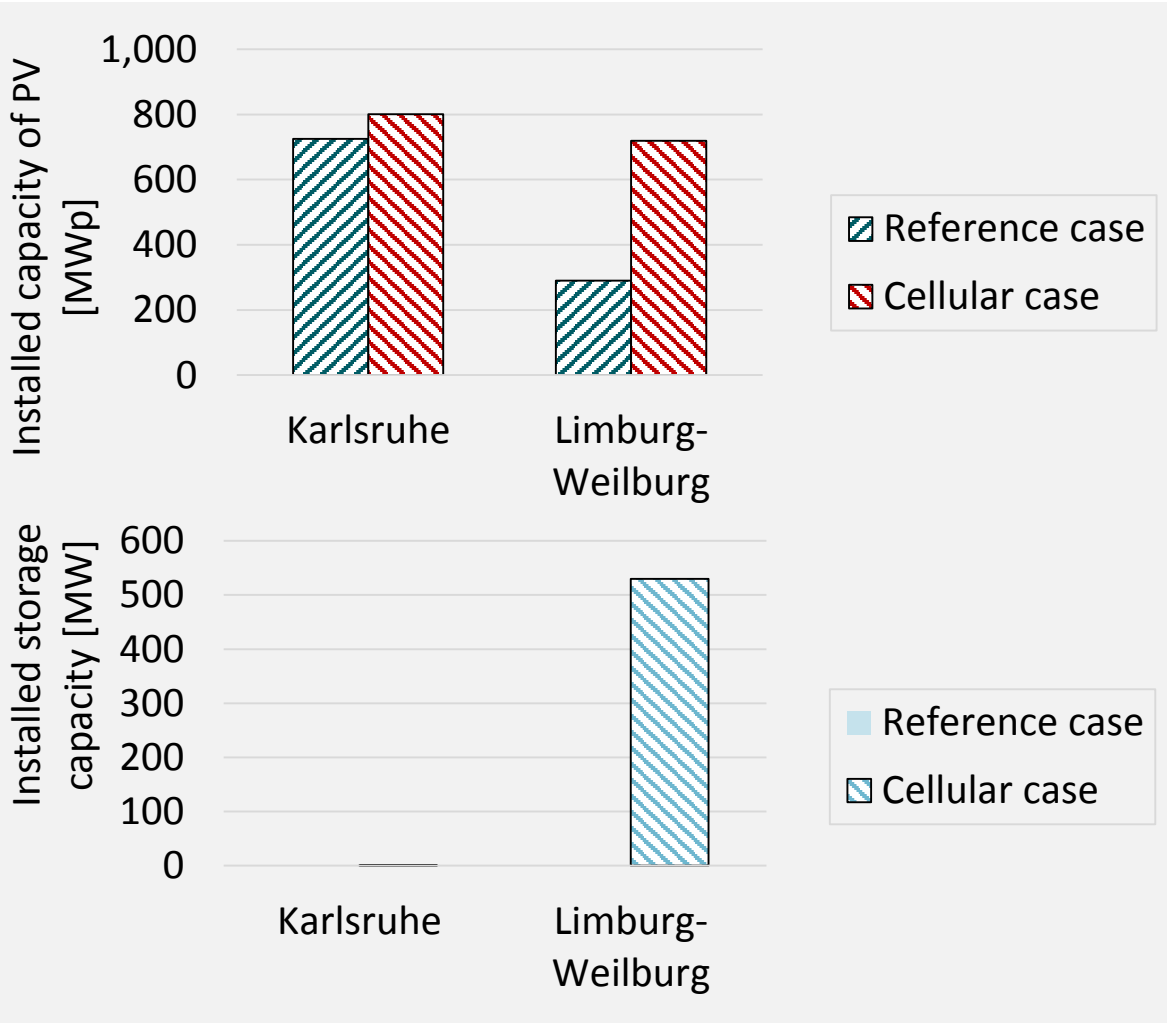
Case Study Results: Optimal capacity of PV and battery storage

- Predefined degree of autonomy not achievable for all cells
- Substantial amounts of PV constructed without a predefined degree of autonomy
- No storage built in Reference Case

	Karlsruhe		Limburg-Weilburg	
	Reference Case	Cellular Case	Reference Case	Cellular Case
Degree of autonomy	32.43%	34.06%	35.50%	60.00%



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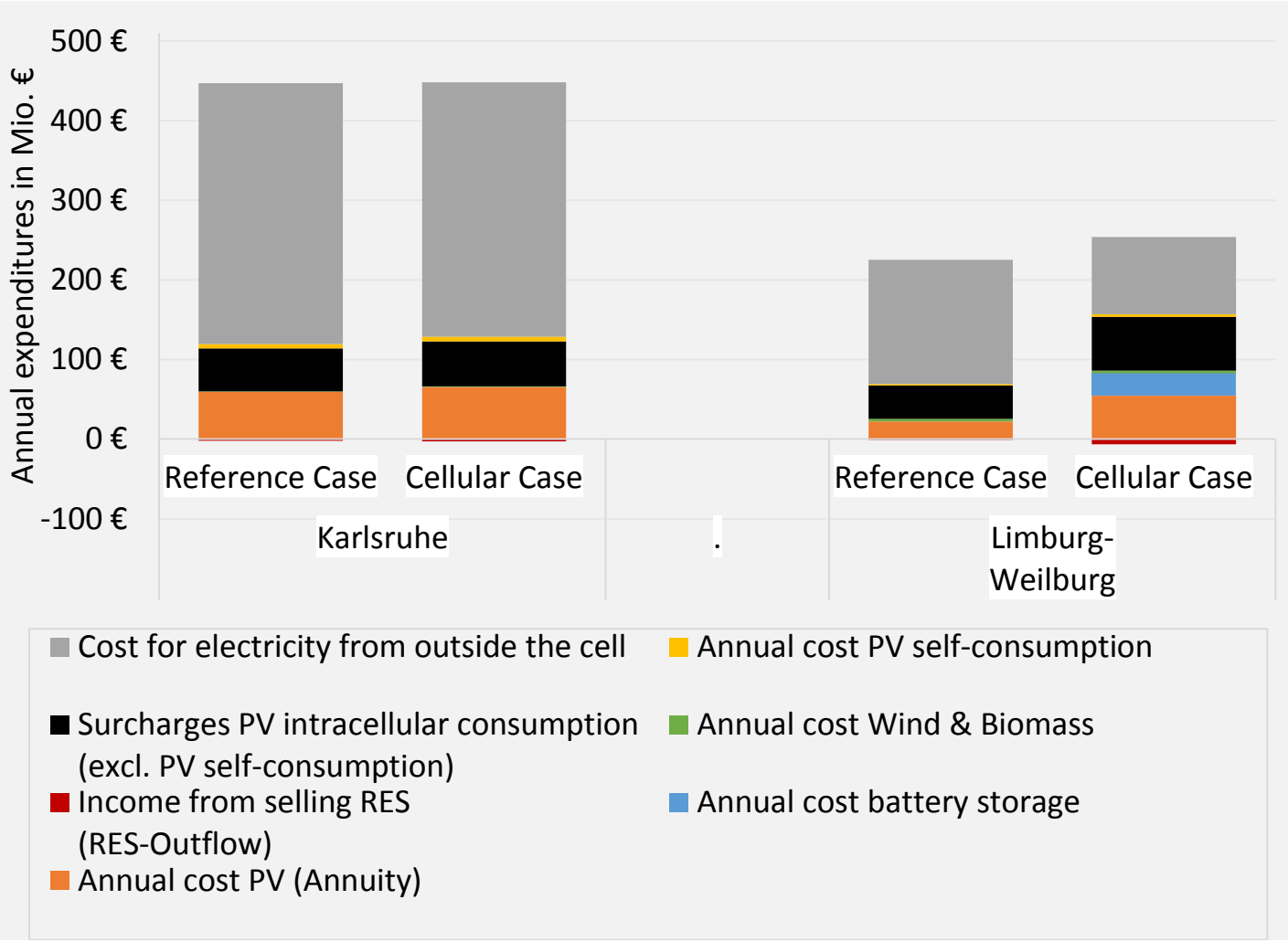
Case Study Results: Expenditures for reference and cellular case

- Cost structure very diverse depending on regional structure
- Electricity purchases account for a large part of total cost
- Profit from selling PV is limited



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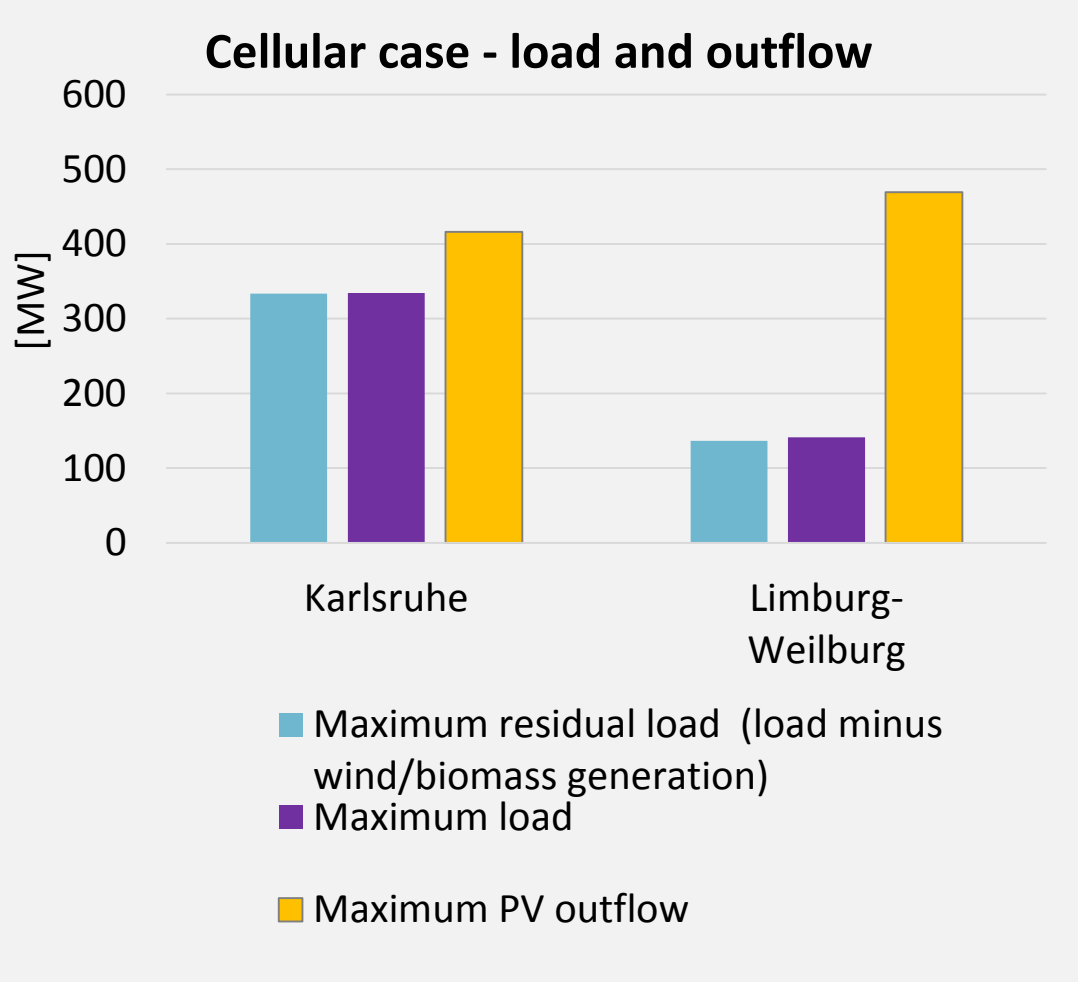
Case Study Results: Autonomy leads to high surplus

- High surplus caused by peaks of PV generation
- Curtailment or transfer to neighboring/superior cells necessary



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Findings and outlook

Findings

- Installing substantial amounts of **PV is economically viable** in all regions
- **Battery storage is not profitable** without a predefined degree of autonomy
- **Defining a high degree of autonomy is feasible in some regions but causes challenges**
  - economically not desirable under the given conditions
  - high amounts of surplus electricity to be handled in neighbouring/superior cells
- Regulatory framework: In cellularly structured regions, PV installations would exceed political objectives

Outlook

- Consider impacts of **other generating technologies**
- Compare battery storage to **other flexibility options**
- Analyze potential **use cases and business case for cellular electricity systems**

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Thank you for your attention

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BACK-UP

Optimization: cost parameters

Specific annual costs for PV and battery storage

	PV rooftop[6]	PV ground-mounted[6]	Battery storage[7]
Spec. cost	850 €/kWp	650 €/kWp	500 €/kWh
Spec. annual cost o&m	20 €/kWp	30 €/kWp	5 €/kWh
Spec. variable cost	0 €/kWp	0 €/kWp	0 €/kWh
Spec. residual value	0 €	0 €	0 €
lifetime	25 y	25 y	15 y
$WACC_{real}$	2,4 %	2,8 %	2,6 %
Annuity	**82,78 €/kWp**	**58,32 €/kWp**	**53,13 €/kWh**

[6] (Fraunhofer ISE 2013, 2015; Vartiainen et al. 2015) [7] (Schmidt et al. 2017, GIZ 2015; IE Leipzig 2014; Sandia National Laboratories 2015).

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Annual expenditures in the target function

Annual cost for PV and battery storage:

- annuity of capital value
- contains investment, reinvestment for the exchange of components, o&m costs, residual value
- distinction between rooftop PV and ground-mounted PV

Annual cost for wind and biomass plants:

- Installed capacity is an input parameter to the model
- fix costs for produced electricity – given as LCOE

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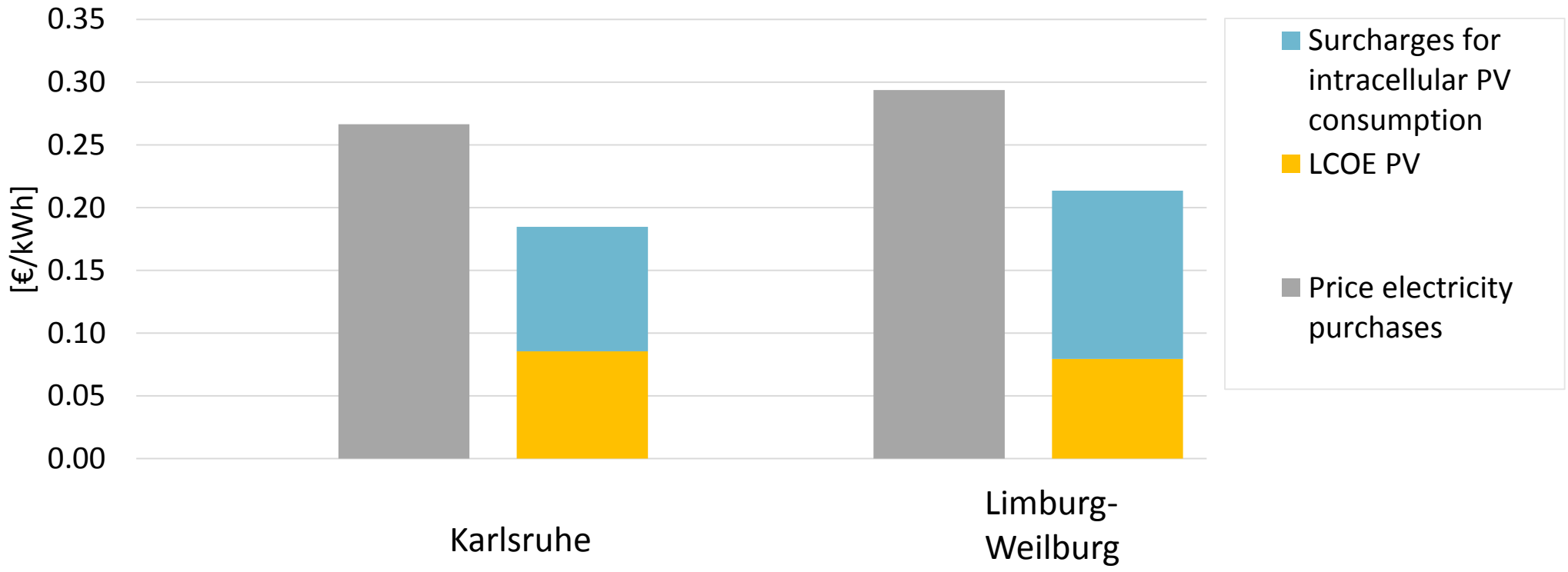
Specific electricity prices



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Methodology: Structure Analysis (1/2): Scope

Objective: Structure analysis of regions

- Classification of NUTS-3 regions based on structure of demand and supply
- Construction of homogenous clusters

Identification of suitable parameters for a cluster analysis:

- Identification of generators and consumer groups with a characteristic profile (high influence on hourly demand and supply of region)
  - Consideration of regionally installed capacity for wind and biomass & potential for PV
  - Assessment of demand structure by examining process load profiles

Conducting a cluster analysis:

- Agglomerative hierarchical clustering procedure according to *Ward*
- Result: NUTS-3 regions are distributed into 6 clusters

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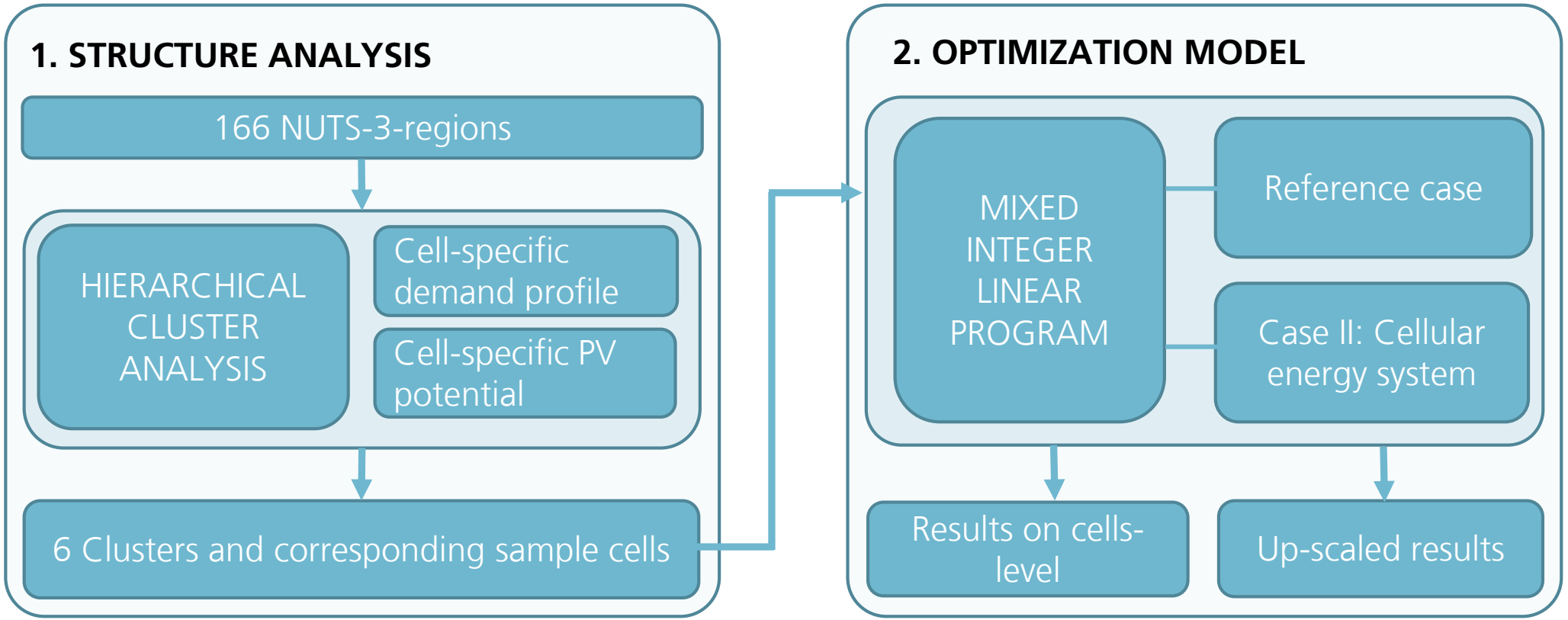
Approach



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