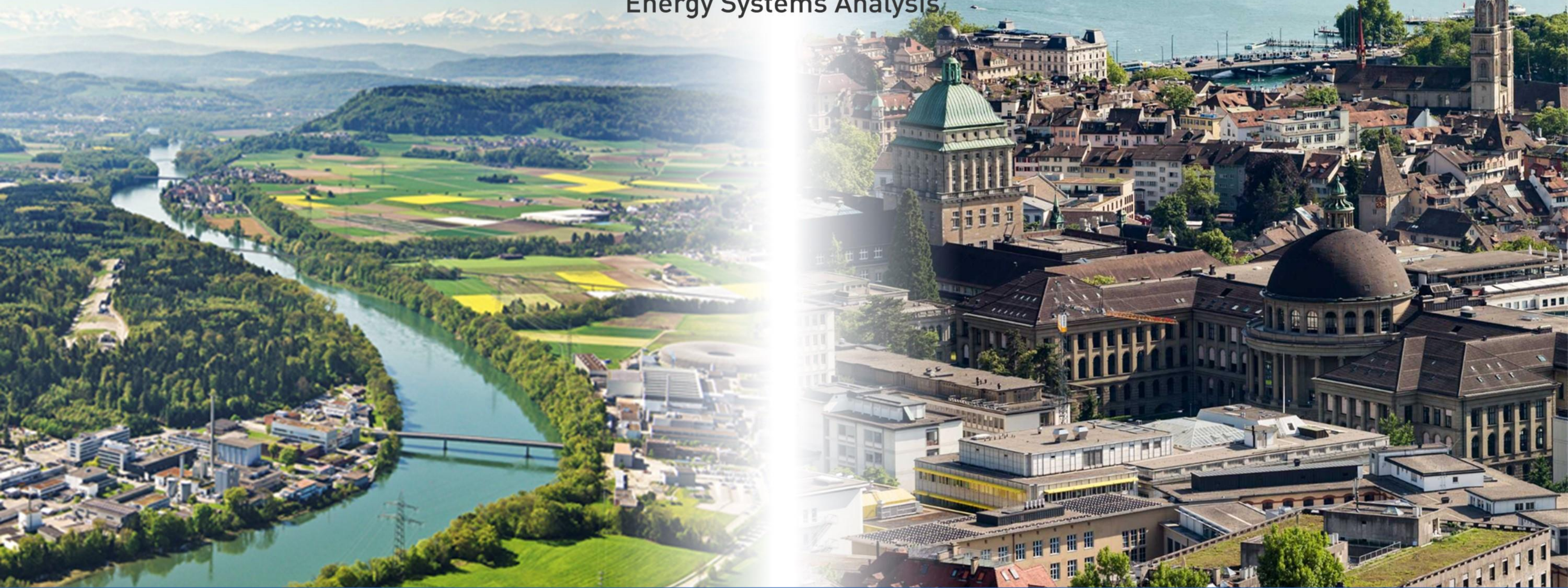
PAUL SCHERRER INSTITUT PSI

ESA Energy Systems Analysis

ETH zürich



Exploring residential energy demand dynamics in the context of the energy transition

Prof. Dr. Russell McKenna, Keynote at ENERDAY 2024, 12th April 2024, Dresden

Integrated Energy Systems Analysis at PSI and ETH

TA

Technology Assessment
Dr. P. Burgherr

5 Scientists
2 Postdocs
5 PhDs

- Life cycle and sustainability analysis
- MCDA
- Internal / external costs
- Health impacts
- Comparative risk assessment

EE

Energy Economics
Dr. N. N.

5 Scientists
4 PhDs
1 Postdoc

- Energy technology development
- Scenario analysis
- Policies strategies for sustainable energy systems

RHR

Risk and human reliability
Dr. V. N. Dang

3 Scientists

- Human Reliability analysis
- Probabilistic safety assessment
- Critical infrastructure and resilience

ESA

Energy Systems Analysis D-MAVT
Prof. Russell McKenna

2 Postdocs
6 PhDs
2 Student Assistants

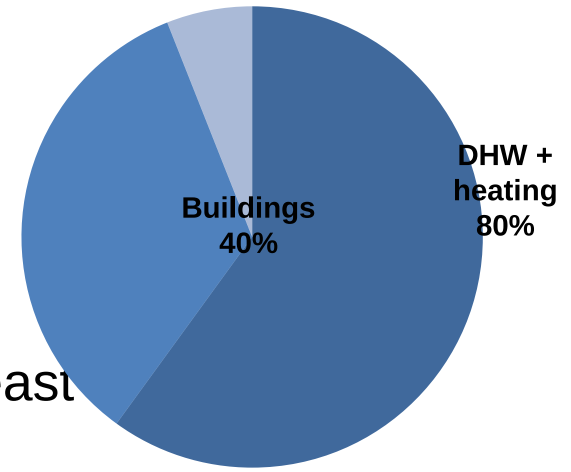
- Decentralised energy systems
- Energy demand
- Resource assessment
- Sector coupling

Agenda

1. **Introduction and background on the residential demand side**
2. Some research highlights to address key chellenges
    1. Understanding the demand side / flexibility
    2. Low carbon technology applications and infrastructure
    3. Fully autonomous residential buildings
3. Case study: energy communities in different european frameworks
4. Take home messages

1. Buildings and municipalies as key

- **Buildings:**
  - Account for almost 40% of (German) energy consumption
  - Around 80% for domestic hot water and space heating
  - **Decentralised approaches** required as most (~90%) of heat is generated and used decentrally, renewable energy exploitation at least partly decentralised
- Various **energy-political objectives:**
  - National: e.g. ambitious targets for renewables in electricity and end energy demand; 80% primary energy demand reduction in residential buildings by 2050
  - Regional/local: differs by location, many communal energy concepts
- **Investment decisions** for many technologies at this "lower level"
- **Interactions** between measures at and between these levels: complexity



BMWi 2014

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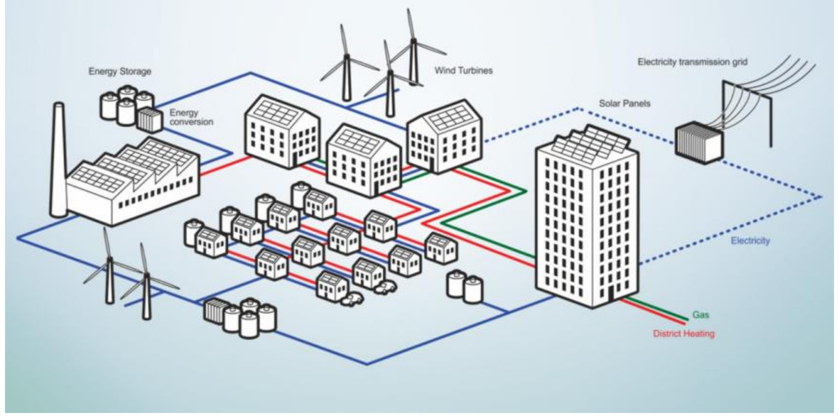
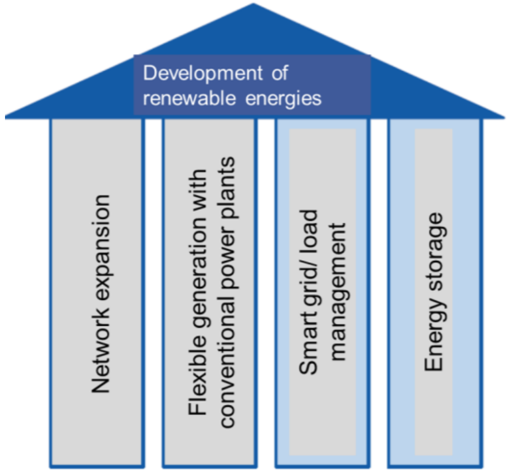
1. Decentralization and renewable energy integration

Characteristic(s)	Centralized	Decentralized
Structure	Linear: generation, transmission/distribution, demand	Integrated: • Vertically, between voltage levels • Horizontally, between energy carriers
Number of power plants	Few large(r) plants	Many small(er) plants
Ownership/actors	Few large(r) companies	Many small(er) owners, e.g. private individuals, farmers
Coordination and control	Generation, transmission and distribution	All areas of system
Predictability	High: supply follows demand	Low: supply and demand largely decoupled
Storage requirements	Low, centralized	High, centralized and decentralized
Flexibility requirements	Low, mainly generation and transmission	Very high

Source: McKenna, R. (2018): The double-edged sword of decentralized energy autonomy, Energy Policy





1. Residential demand side | 2. Research highlights | 3. Energy communities in European framework | 4. Take home messages

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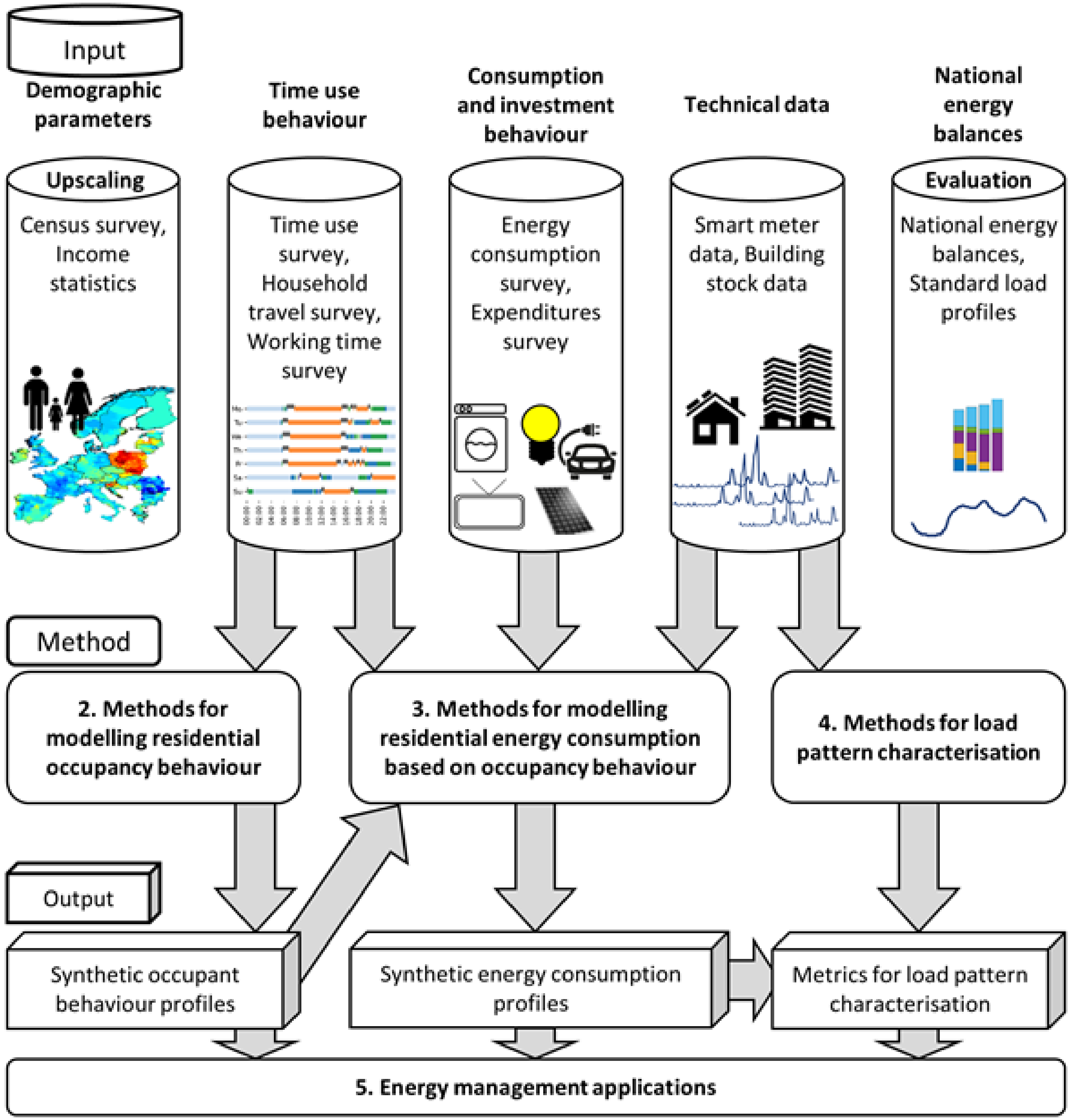
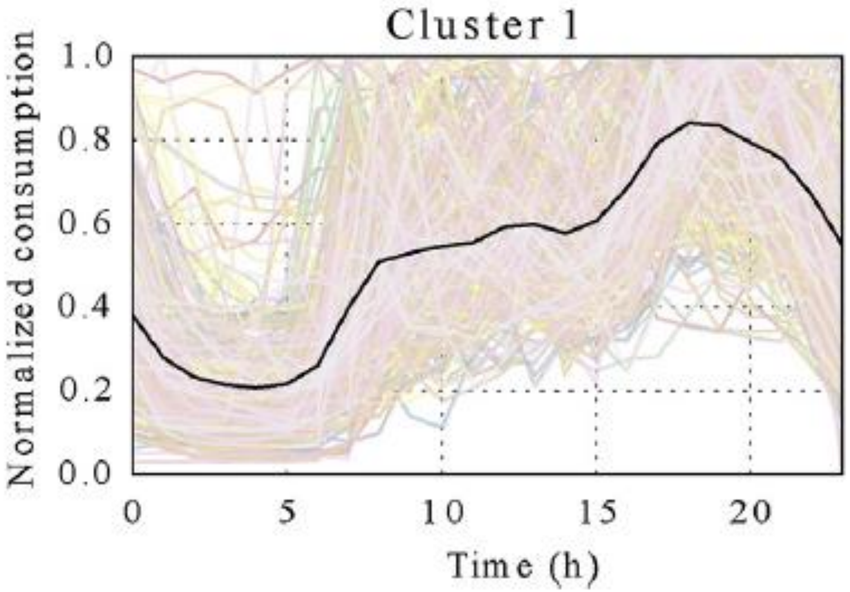
2.1 Understanding the (residential) demand side: overview



Max Kleinebrahm[1], Russell McKenna[2,3,4], Jose L. Ramirez-Mendiola[5], Yohei Yamaguchi[6], Febin Kachirayil[2], Jacopo Torriti[5], Characterization, Simulation and Management of Residential Energy Demand, Chapter in forthcoming Research Handbook of Energy Management, Ed. R. Madlener & V. Bertsch, Edward Elgar.

2.1 Characteristics and flexibility of demand



Source: Viegas et al. 2016

- Increased requirements for energy system flexibility…
- …require deeper understanding of:
  - Different "types" of consumers (or prosumers)
  - Their charactersitics, e.g. flexibility, energy profiles
  - The interaction between these types
  - The ways in which LCTs could diffuse and their impacts
- It is helpful to disguish between shorter and longer timeframes:
  - Short term: periods of hours, days and weeks: demand profiles
  - Longer term: periods of years and decades: household decisions (e.g. investment)
- Methods:
  - Short-term: e.g. smart meter data clustering/classification, bottom-up simulations
  - Long-term: e.g. more realistic modelling of behaviour, e.g. surveys/questionnaires combined with agent-based (ABM) or system dynamics (SD) approaches

ESM: Energy System Model, LCT: Low Carbon Technology

2.1 CREST HEAT AND POWER (CHAP) simulation

- Extends CREST electricity simulation model, based on time-use data and Markov chains
- Reduced order thermal model based on 2-node thermal model of Nielsen (2005)
- Maps to the whole UK building stock through Cambridge Housing Model
- Heating patterns based on empirical data and occupancy patterns (EFUS)
- Inputs:
  – Static: thermal characteristics of the dwelling, no. of occupants, heating pattern
  – Dynamic: climate (temperature and irradiaton)
- Open source development: http://www.iip.kit.edu/3559.php

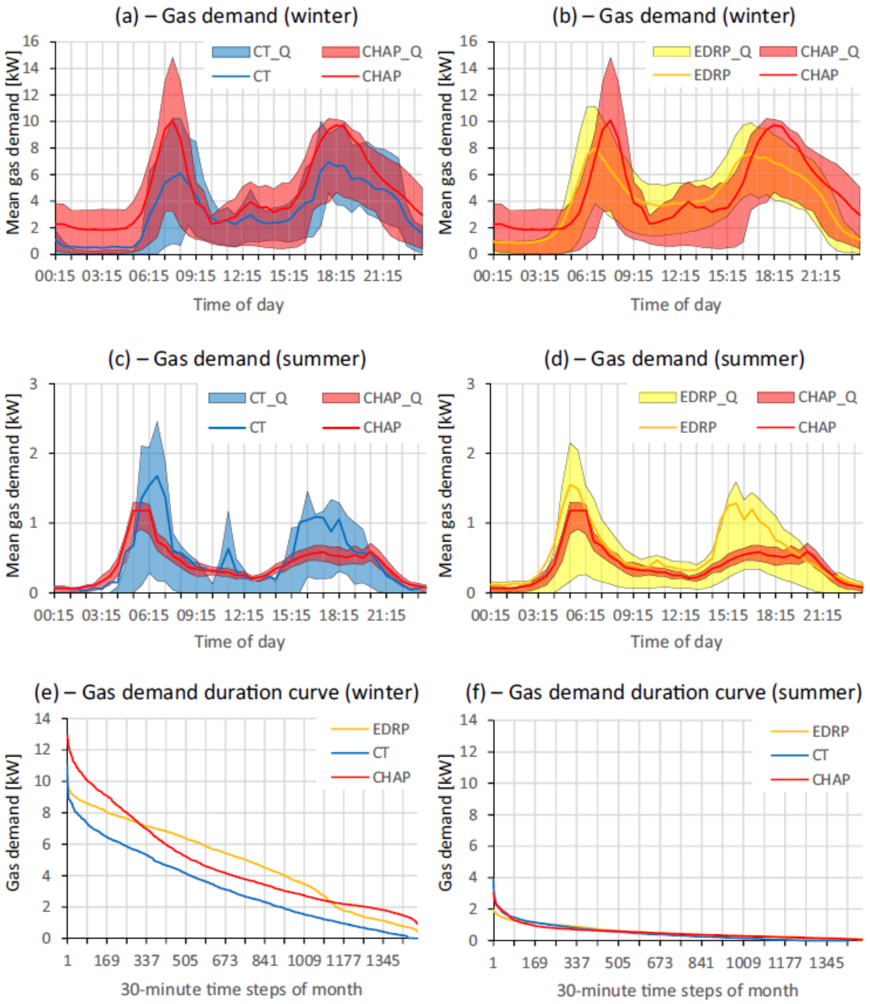


Fig. 12. Validation of the CHAP model's weighted mean gas demand with EDRP and CT empirical datasets.

McKenna, R., Hofmann, L., Kleinebrahm, M., Fichtner, W. (2018): A stochastic multi-energy simulation model for UK residential buildings, Energy and Buildings, 168, 470-489, https://doi.org/10.1016/j.enbuild.2018.02.051.

2.1 Exploiting flexibility and DSM: Value of Lost Load

- The Value of Lost Load (VOLL) is a key metric to assess the economic impact of power supply interruptions
- Current EU regulations recommend a single average value per country
- This study derives county-level Value of Lost Load estimates at an hourly resolution for the residential sector in Germany through a production function approach.
- Load curtailment options at different costs are integrated into an urban energy system optimization model to evaluate their effects on system cost and reliability indicators.

Residential energy systems, Room: HSZ/405/H, 14:55

Febin Kachirayil, David Huckebrink, Valentin Bertsch, Russell McKenna, Trade-offs between system cost and supply security in municipal energy system design: an analysis considering spatio-temporal disparities in the Value of Lost Load, under review with Applied Energy, April 2024

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2.2 Low Carbon Technology diffusions and effects of socioeconomic differentiation on residential load profiles

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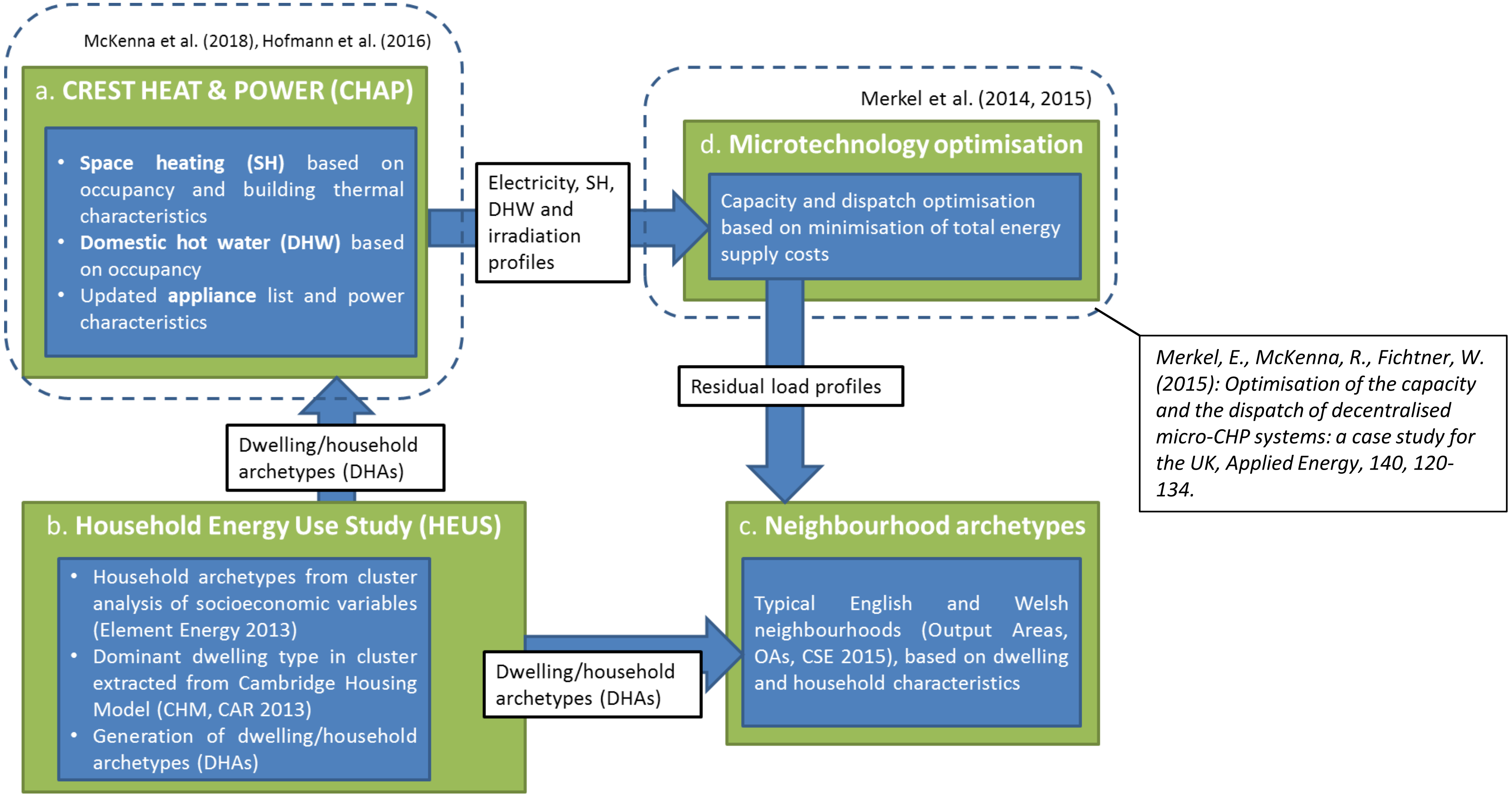
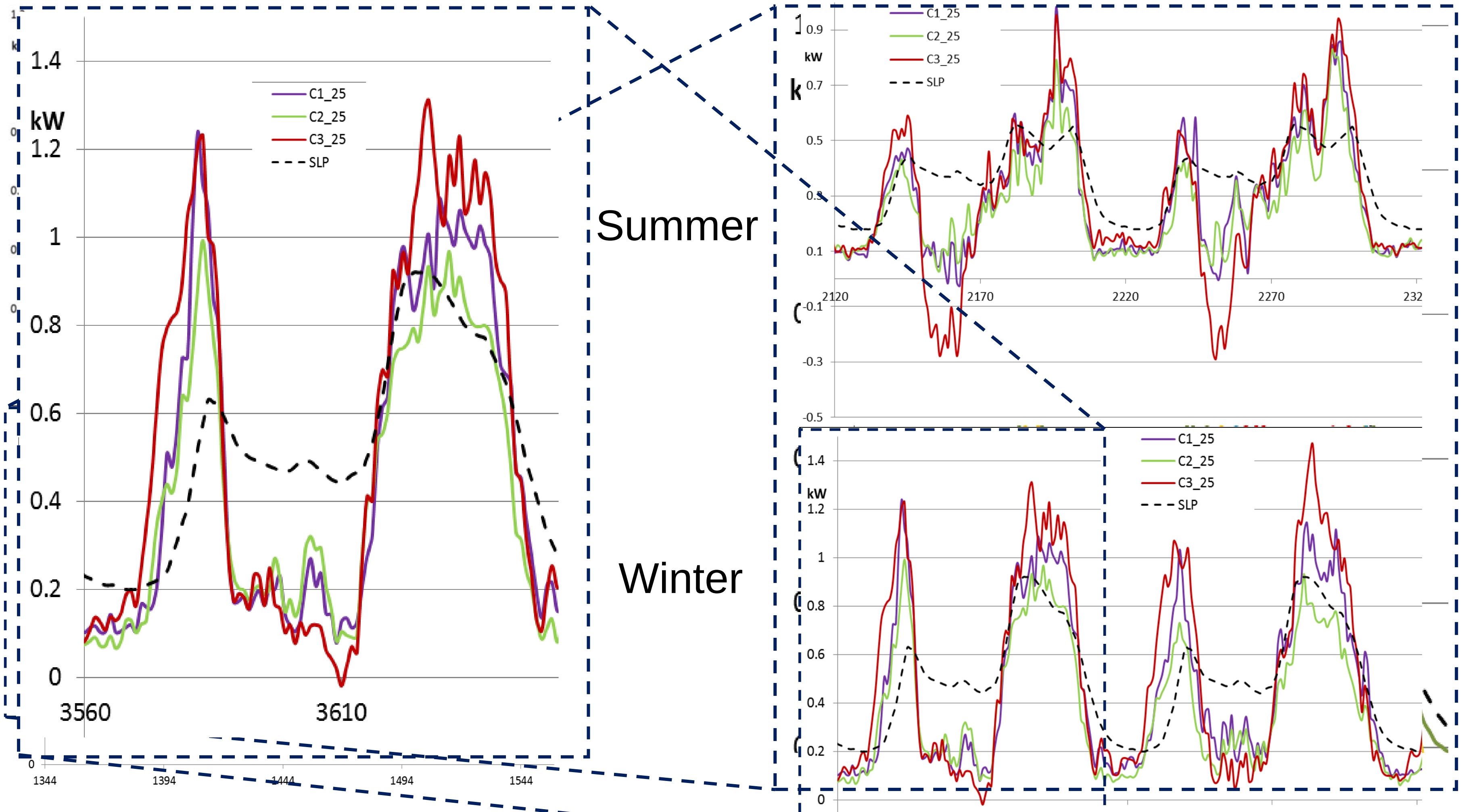


McKenna, R., Hofmann, L., Merkel, E., Fichtner, W., Strachan, N. (2016): Analysing socioeconomic diversity and scaling effects on residential electricity load profiles in the context of low carbon technology uptake, Energy Policy, 97, pp. 13-26 10.1016/j.enpol.2016.06.042
McKenna, R., Djapic, P, Weinand, J., Fichtner, W., Strbac, G. (2018): Assessing the implications of socioeconomic diversity for low carbon technology uptake in electrical distribution networks, Applied Energy, 210, 856-869, https://doi.org/10.1016/j.apenergy.2017.07.089

2.2 Low Carbon Technology diffusions and effects of socioeconomic differentiation on residential load

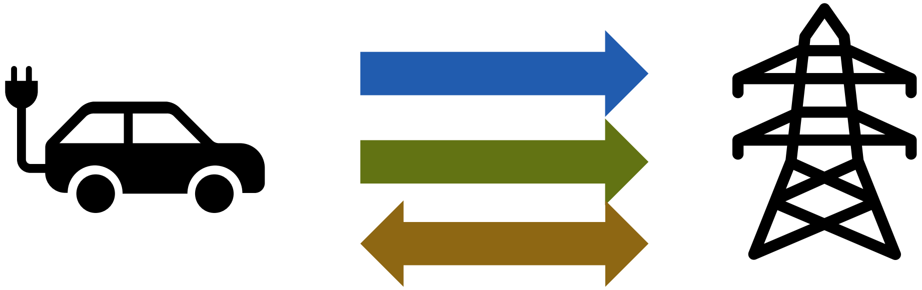
Penetration of LCTs in a UK neighbourhood: Reference Scenario (left) and 25% Scenario (right)



SLP: Standard Load Profile

McKenna, R., Hofmann, L., Merkel, E., Fichtner, W., Strachan, N. (2016): Analysing socioeconomic diversity and scaling effects on residential electricity load profiles in the context of low carbon technology uptake, Energy Policy, 97, pp. 13-26 10.1016/j.enpol.2016.06.042

2.2 EV charging strategies vs. infrastructure costs



	Charging	Timing
Passive charging (PC)	Unidirectional	Not flexible
Smart charging (SC)	Unidirectional	Flexible
Vehicle-to-grid (V2G)	Bidirectional	Flexible

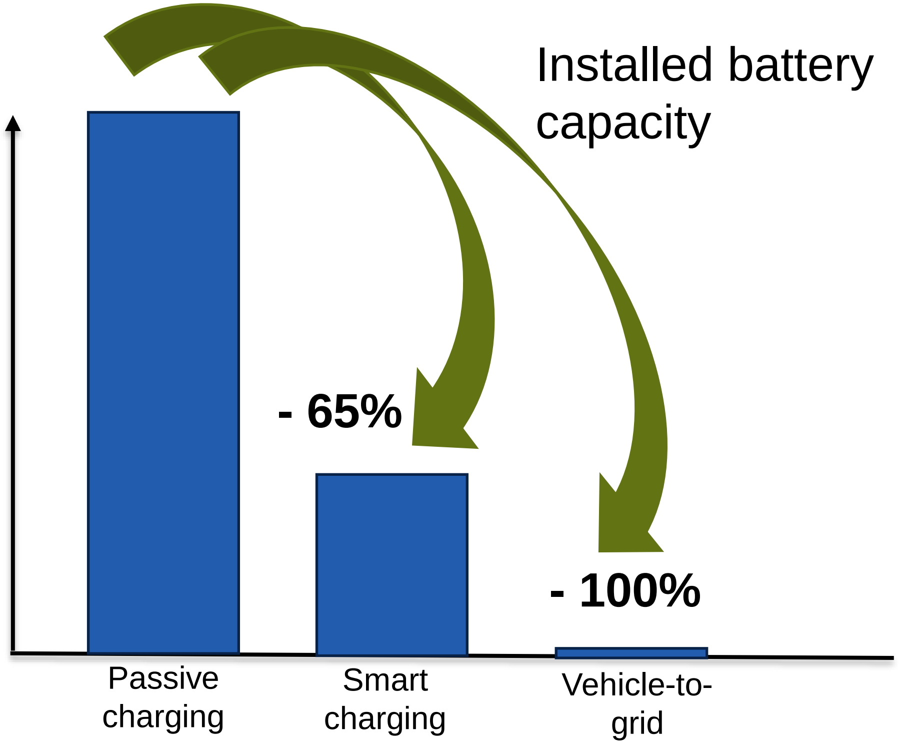
- Electric vehicles are considered essential to decarbonize private mobility sector
- Their widespread adoption could increase peak loads significantly
- Charging strategy has the potential to impact energy systems greatly

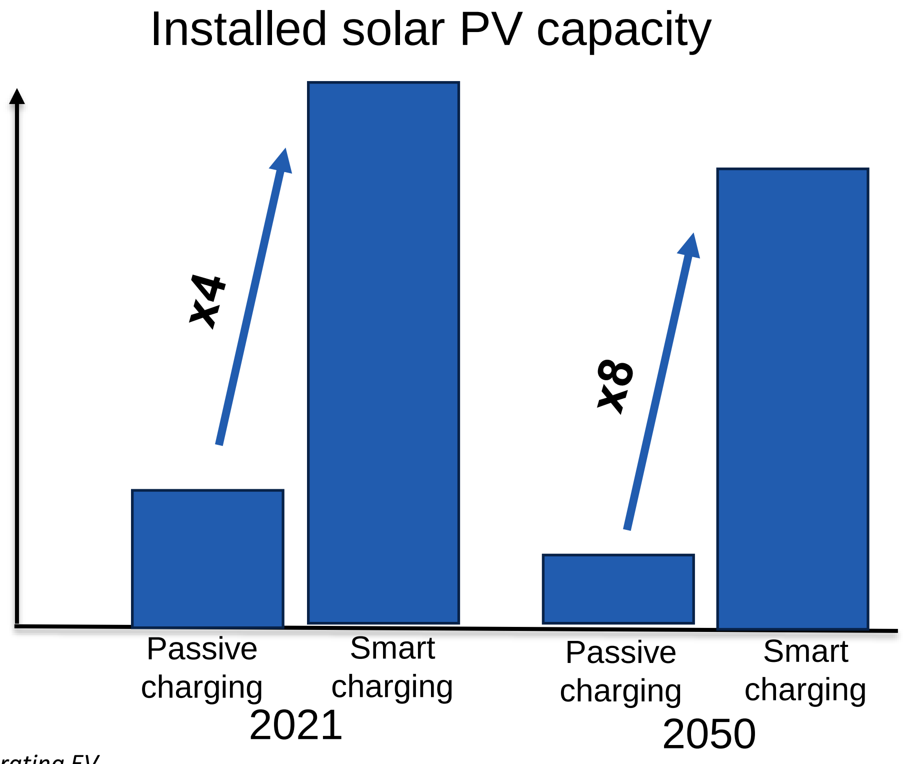
Linda Brodnicke, Febin Kachirayil, Paolo Gabrielli, Giovanni Sansavini, Russell McKenna, Integrating EV charging behaviour into a municipal energy system model to explore trade offs between flexibility and battery degradation, under preparation for Applied Energy

How do EV charging strategies impact the **flexibility requirements** and **renewable integration** of decentralized energy systes?

2.2 Flexible EV charging increases PV share and decreases flexibility needs

- Much more PV installed under flexible charging than PC (but no real difference between SC and V2G)
- V2G removes need for dispatchable biomass generation and shifts to reliance on imports, which increase by nearly as much as biomass could generate in a year



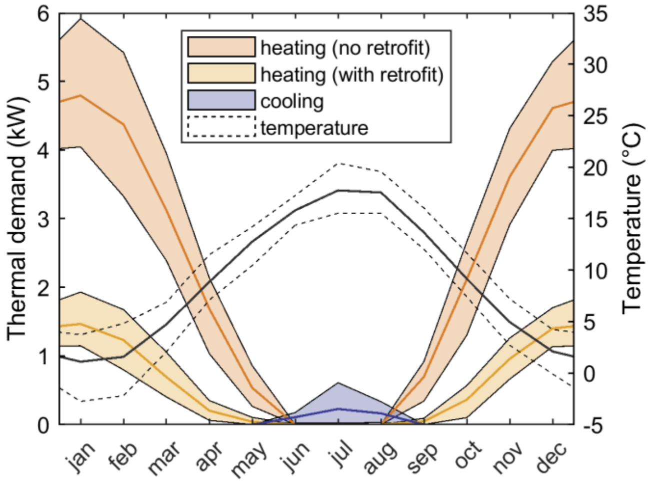


Linda Brodnicke, Febin Kachirayil, Paolo Gabrielli, Giovanni Sansavini, Russell McKenna, Integrating EV charging behaviour into a municipal energy system model to explore trade offs between flexibility and battery degradation, under preparation for Applied Energy

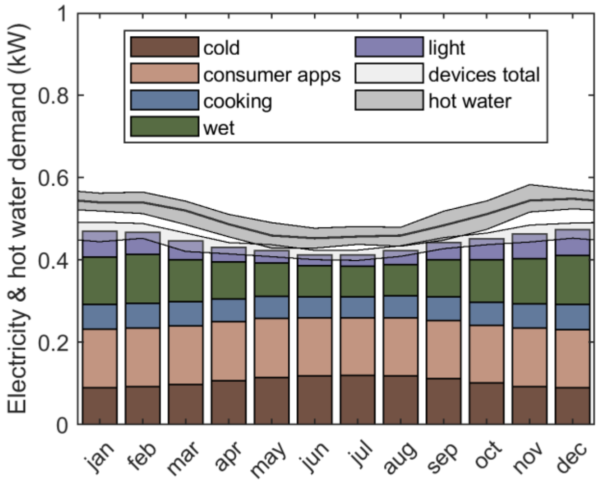
2.3 Energy autonomous Single Family Houses (SFHs)

- Rising energy procurement costs and declining capital costs for renewable technologies provoke interest in self-sufficiency
- Besides perceived financial benefits, the pursuit of self-sufficiency most influences households' intentions to purchase renewable energy technologies
- Main challenge: seasonal mismatch between building energy demand and renewable supply
- Is there a techno-economic potential for 100% self-sufficient residential buildings in Europe?

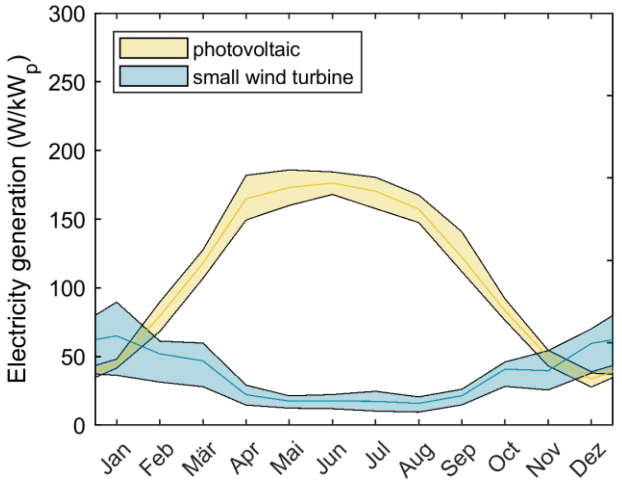
Thermal demand



Electricity & hot water



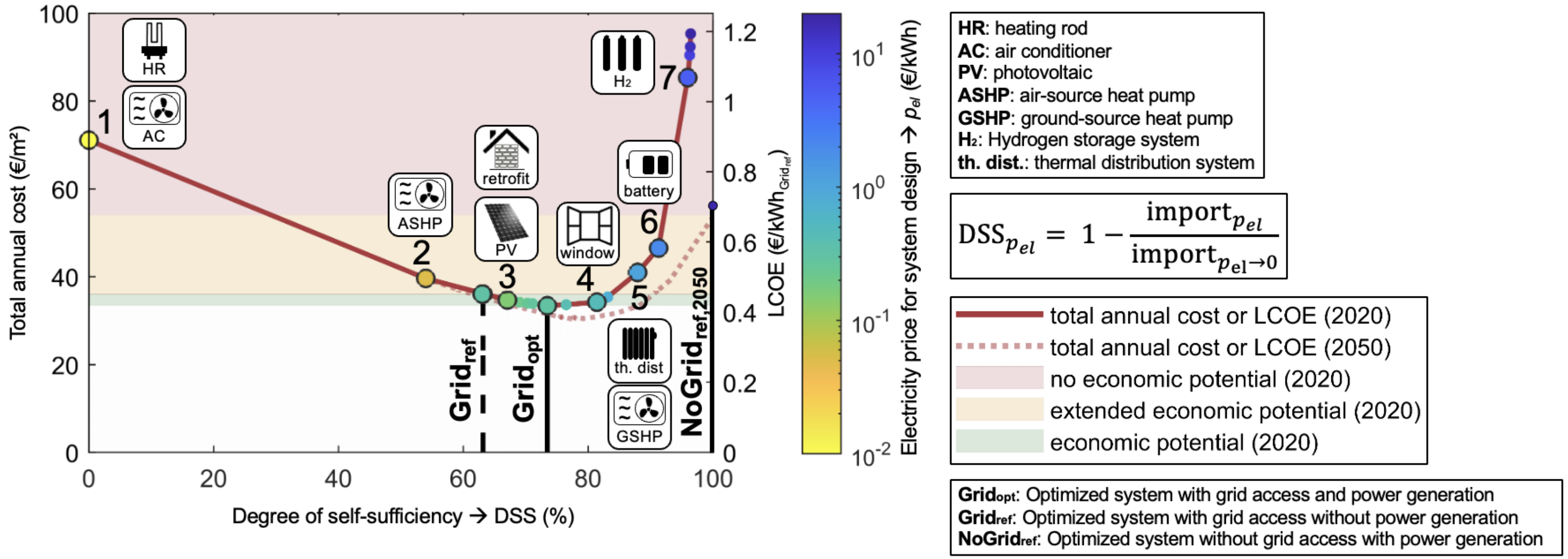
Energy supply



Two million European single-family homes could abandon the grid by 2050, Max Kleinebrahm, Jann Michael Weinand, Elias Naber, Russell McKenna, Armin Ardone and Wolf Fichtner, Joule, vol. 7: no. 11, pp. 2485-2510, Cell Press, 2023.DOI: 10.1016/j.joule.2023.09.012

2.3 Energy autonomous SFHs: results for Germany

- At very low energy carrier prices, it is advantageous to import all of the energy required
- Very high energy carrier prices lead to a minimization of energy imports and useful energy demand through efficiency measures and maximization of self-generation
- Significantly rising costs at self-sufficiency levels > 90% → but less pronounced in 2050



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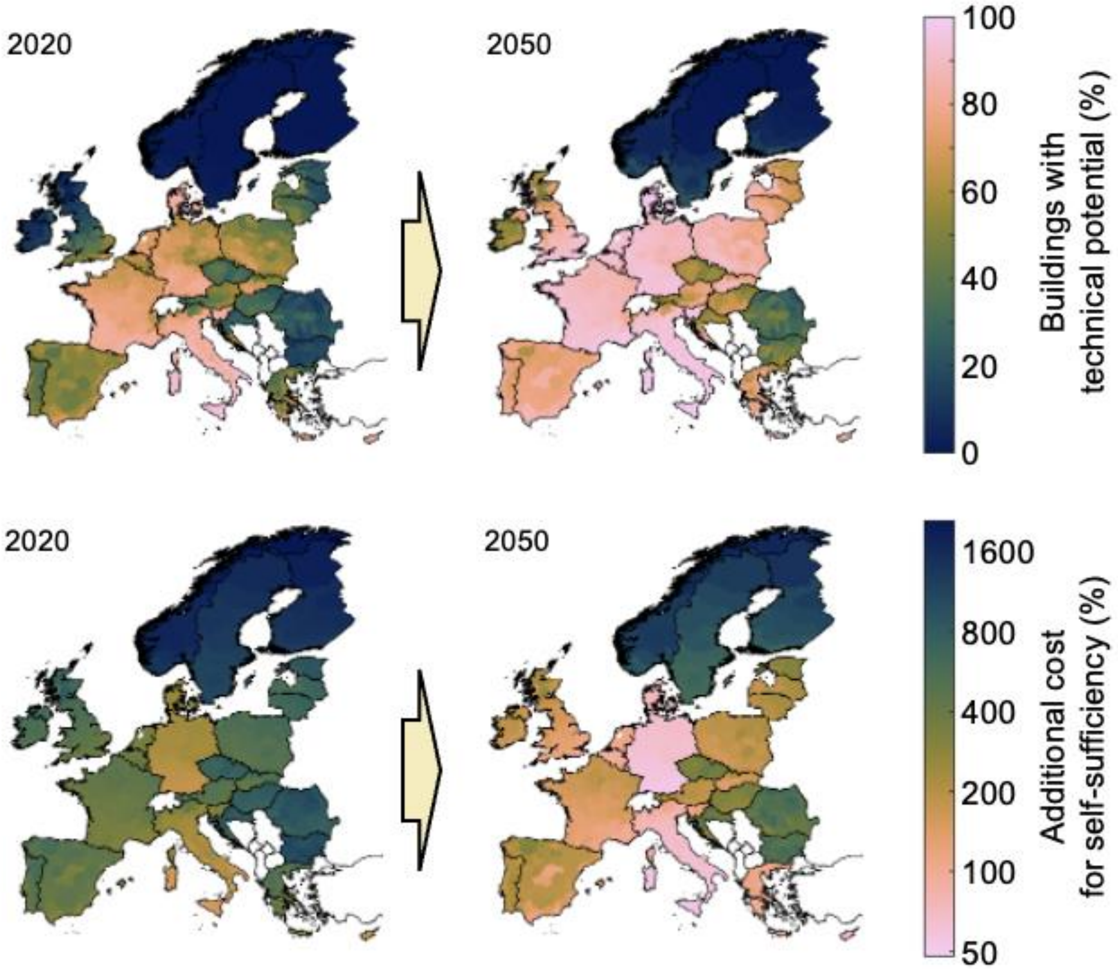
2.3 Autonomous SFHs: European potential

Technical potential

- Heat and electricity supply based on the roof area potential
- **53%** of the 41 million single-family homes examined in **2020**
- **75%** of the 41 million single-family homes examined in **2050**



Economic potential

- No economic potential in 2020 (0%) and 2050 (<< 1%)
- If building owners would be willing to pay 50% more in 2050 (w.r.t. $Grid_{ref}$)

Extended economic potential for 2 million buildings

Two million European single-family homes could abandon the grid by 2050, Max Kleinebrahm, Jann Michael Weinand, Elias Naber, Russell McKenna, Armin Ardone and Wolf Fichtner, Joule, vol. 7: no. 11, pp. 2485-2510, Cell Press, 2023.DOI: 10.1016/j.joule.2023.09.012

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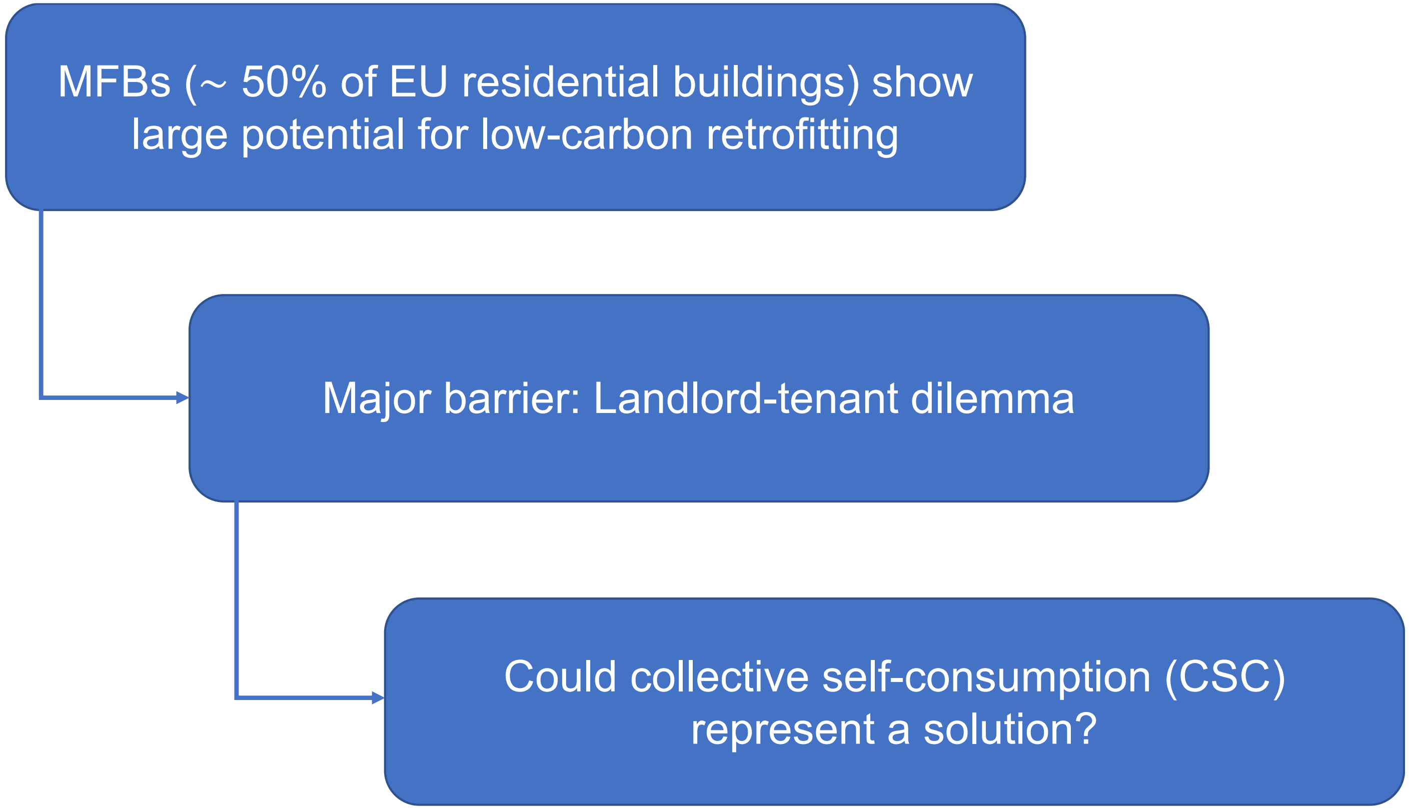
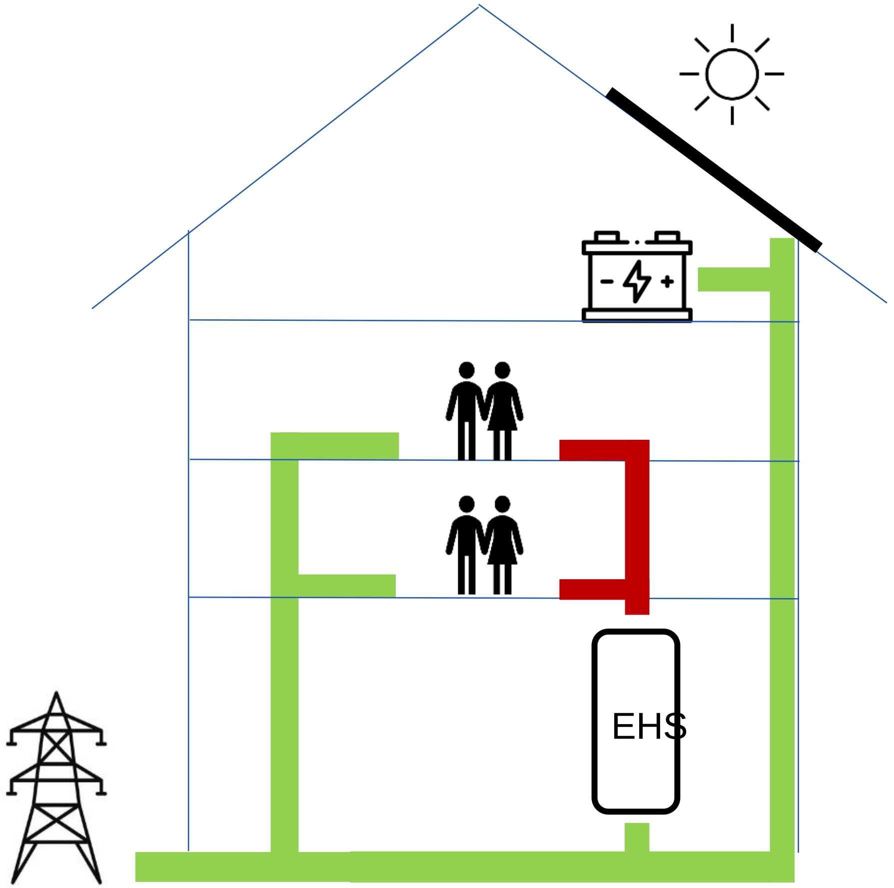
3. Landlord-tenant dilemma in multi-family buildings (MFBs) represents a significant problem for addressing climate change



Overcoming the landlord-tenant dilemma: a techno-economic assessment of collective self-consumption for European multi-family buildings, Christoph Domenig, Fabian Scheller, Philipp Gunkel, Julian Hermann, Claire Bergaentzlé, Marta Lopes, Jacob Barnes, Russell McKenna, in press with Energy Policy, April 2024

3. Collective self-consumption in MFBs could represent a promising solution



Who?
Cooperating owners and renters located in same building

What?
Aggregating production and consumption profiles, trading local electricity

Why?
Additional owner revenue and renter savings

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3. Literature overview and research gap

Table 3: Overview of selected papers relevant to the current study.

Author	Country[a]	Spatial level[b]	CSC Regulation: Exemptions[c]	CSC Regulation: Surplus Remun.	Senstivities[d]: CL	EC	BE	RF	Model Features[e]: SI	HPI	PR
Lindberg et al. (2016)	DE	MFB	PX	fixed FiT		x				x	
Niemelä et al. (2017)	FI	MFB	FX	zero						x	x
Wu et al. (2017)	CH	MFB	FX	fixed FiT			x			x	x
Fina et al. (2018)	DE/AT	MFB	FX	fixed FiT		x			x		
Fina et al. (2019)	AT	MFB	FX	fixed FiT		x	x			x	x
Ferrara et al. (2019)	IT	MFB	FX	monthly FiT		x				x	x
Fleischhacker et al. (2019)	US	MFB	FX	market price		x		x	x		
Pinto et al. (2020)	ES	MFB	FX/PX	various				x		x	
Radl et al. (2020)	8 EU MS	NH	FX/PX	market price	x	x					
Fina et al. (2021)	AT/AU	MFB	FX	zero	x	x					
Garavaso et al. (2021)	IT	MFB	PX + subsidy	fixed FiT				x		x	x
Gallego-Castillo et al. (2021)	ES	MFB	FX	zero/net billing	x	x		x			
Herencic et al. (2021)	HR	NH	FX/PX	net billing/metering				x			
Roberts et al. (2022)	AU	MFB	FX	not considered					x		
Braeuer et al. (2022)	DE	MFB	FX + subsidy	fixed FiT			x	x	x	x	
Canova et al. (2022)	IT	MFB	PX + subsidy	market price	x					x	
Villalonga Palou et al. (2023)	ES	MFB	FX	net billing		x					
Mansó Borràs et al. (2023)	PT	NH	FX	monthly market avg.			x				
Gil Mena et al. (2023)	ES	MFB	FX	zero/net billing				x			
Belmar et al. (2023)	PT	District	FX	monthly market avg.				x			
Kühn et al. (2023)	DE	MFB	FX + subsidy	fixed FiT		x	x		x	x	x

[a]Country abbreviations equivalent to national internet domains, MS=Member States
[b]MFB=Multi-family building, NH=Neighborhood
[c]FX=Full exemption of grid tariffs and taxes, PX=Partial exemption of grid tariffs and taxes
[d]CL=Climate, EC=Energy costs, BE=Building energy efficiency, RF=Regulatory framework
[e]SI=Split incentives, HPI=Heat pump investment, PR=Passive retrofitting

→ Overarching analysis of external influencing factors (technical, economic, climatic etc.) at European level is missing

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3. Research question

1. Under what climatic, techno-economic and regulatory conditions does CSC provide conjoint economic benefits for landlords and renters in MFBs?

2. How do different CSC regulations impact the distribution of benefits and low-carbon technology investment?

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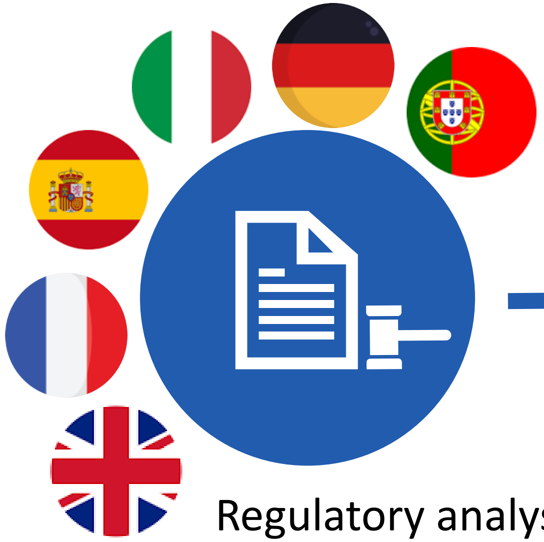
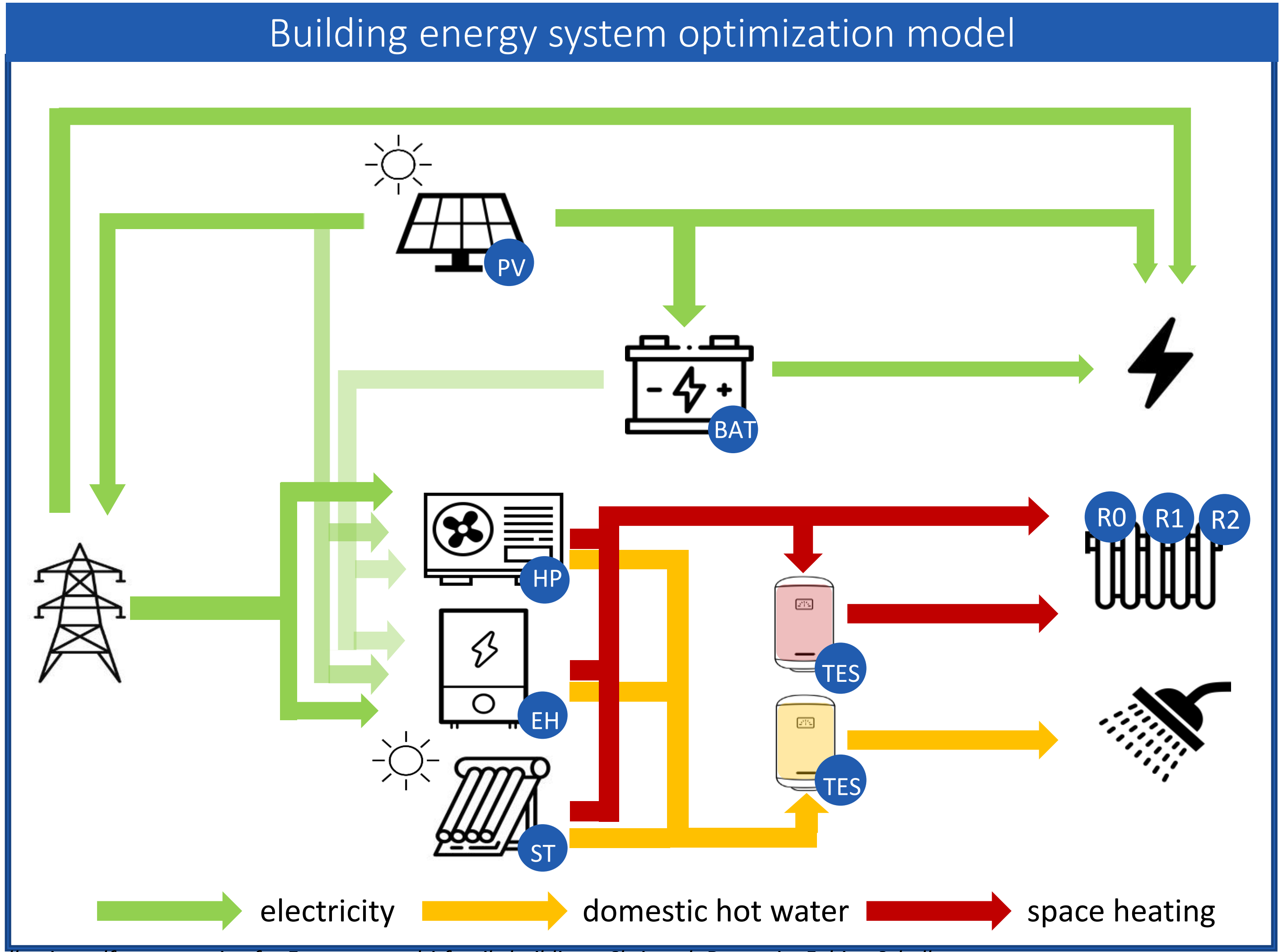
3. Methodology



4 CSC regulatory scenarios

Regulatory analysis of CSC frameworks



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3. Model maximizes NPV to the building owner while guaranteeing savings for renters compared to BAU

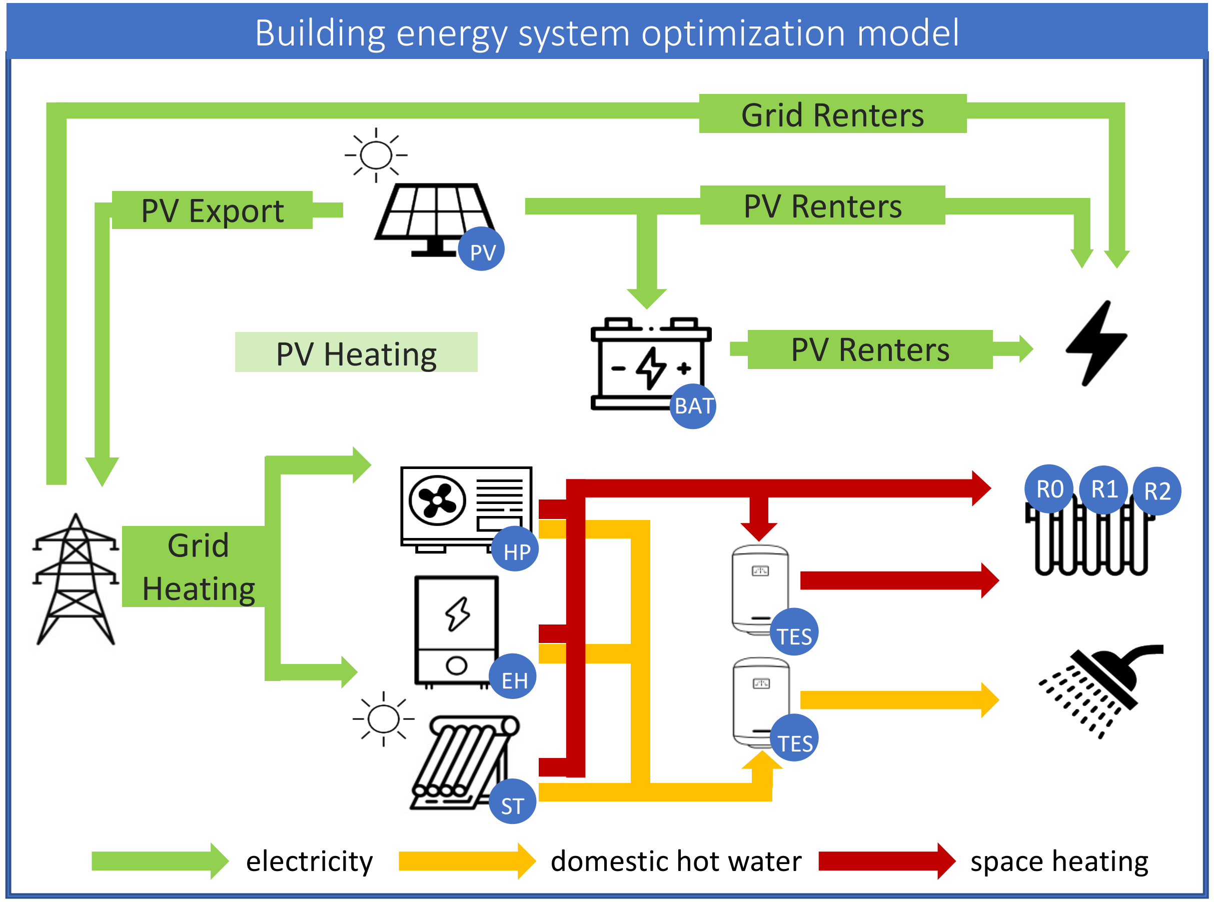
Maximize:

NPV of Building Owner =

- \- Active Retrofit Investment
- \- Passive Retrofit Investment
- \- PV and Battery O&M Costs
- \+ PV Cash flows
- \+ Rent Increase

Rent increase <= 8% of (nominal) value active/passive heating upgrades

Rent increase + new heating costs <= 90% of BAU heating costs



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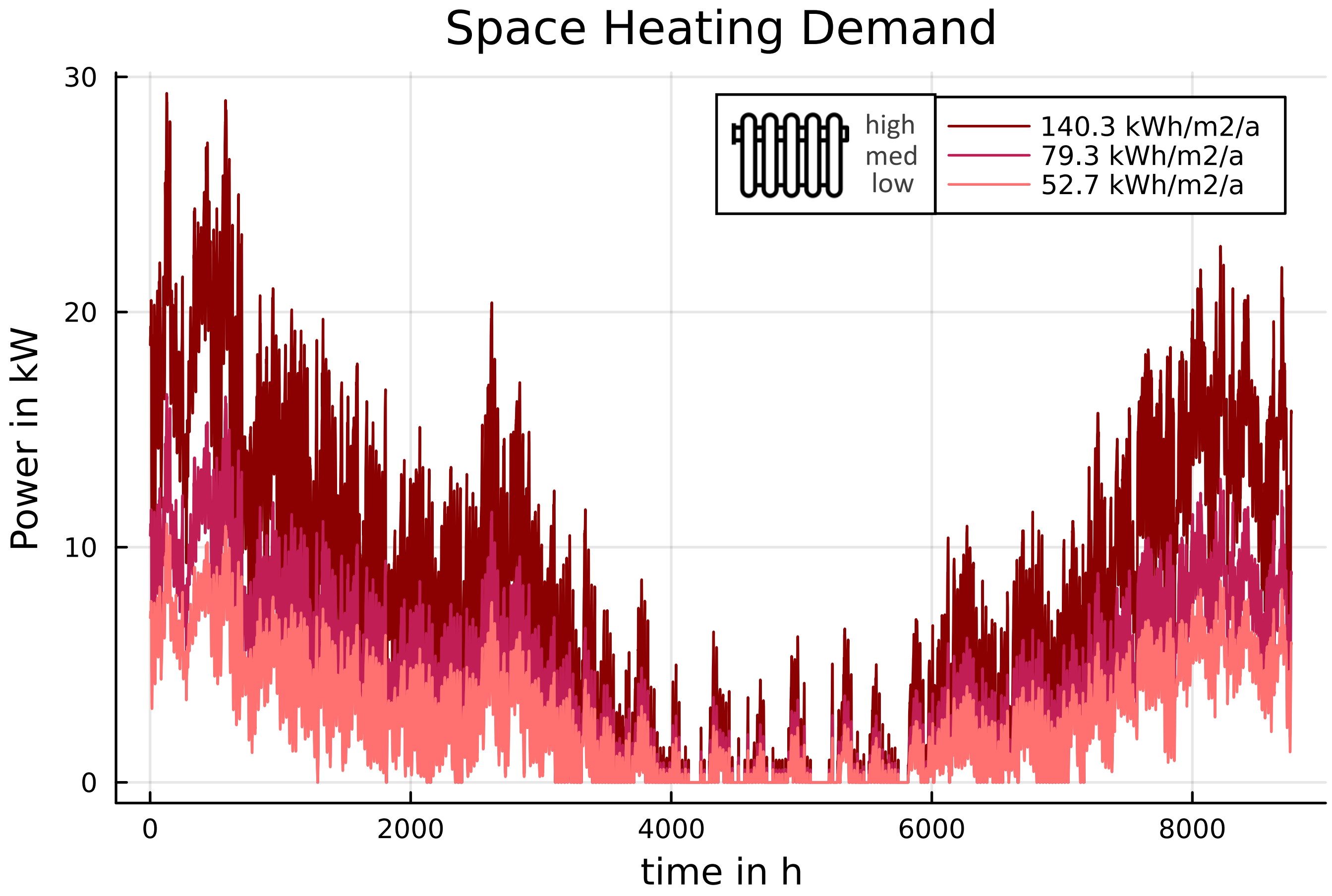
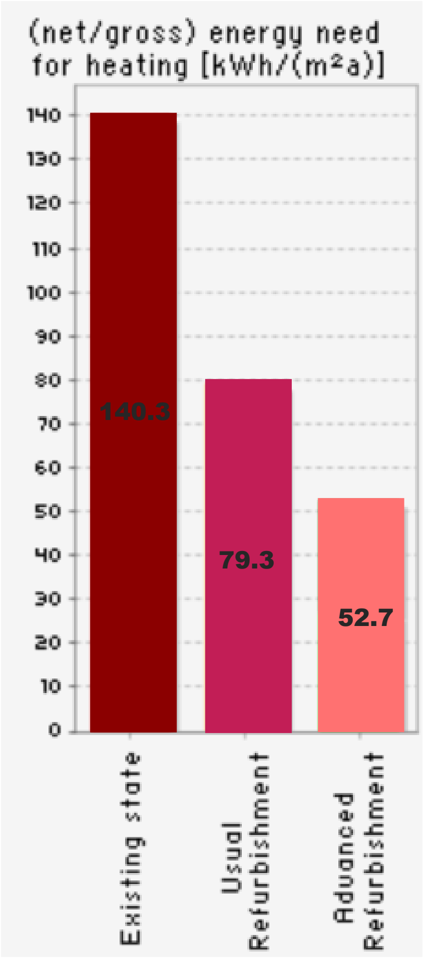
3. Three passive retrofit levels are considered





Building Size Class:

MFH

Construction Period:

1949...1957

Reference Floor Area:

486 m^2

Heat Supply System:

gas central heating, poor efficiency (multi-unit housing)

Climate Region

Default (National (EnEV 2009))

Adapted from Tabula Webtool

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3. European-wide case study design

Power and heat (all technologies):

CSC Policy x Elec-cost x Climate Zone x Heat-cost x MFB envelope η

[Four Scenarios] x [0.2,0.3,0.4]* x [North, Cont, Med] x [0.08,0.12,0.16]* x [low,med,high]

Power only (PV + BAT):

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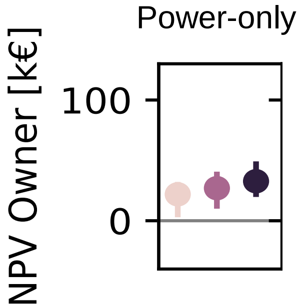
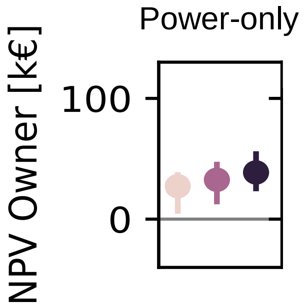
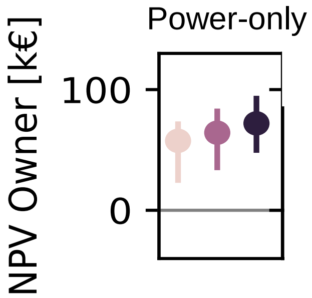
North Atlantic Climate



Continental Climate



Mediterranean Climate



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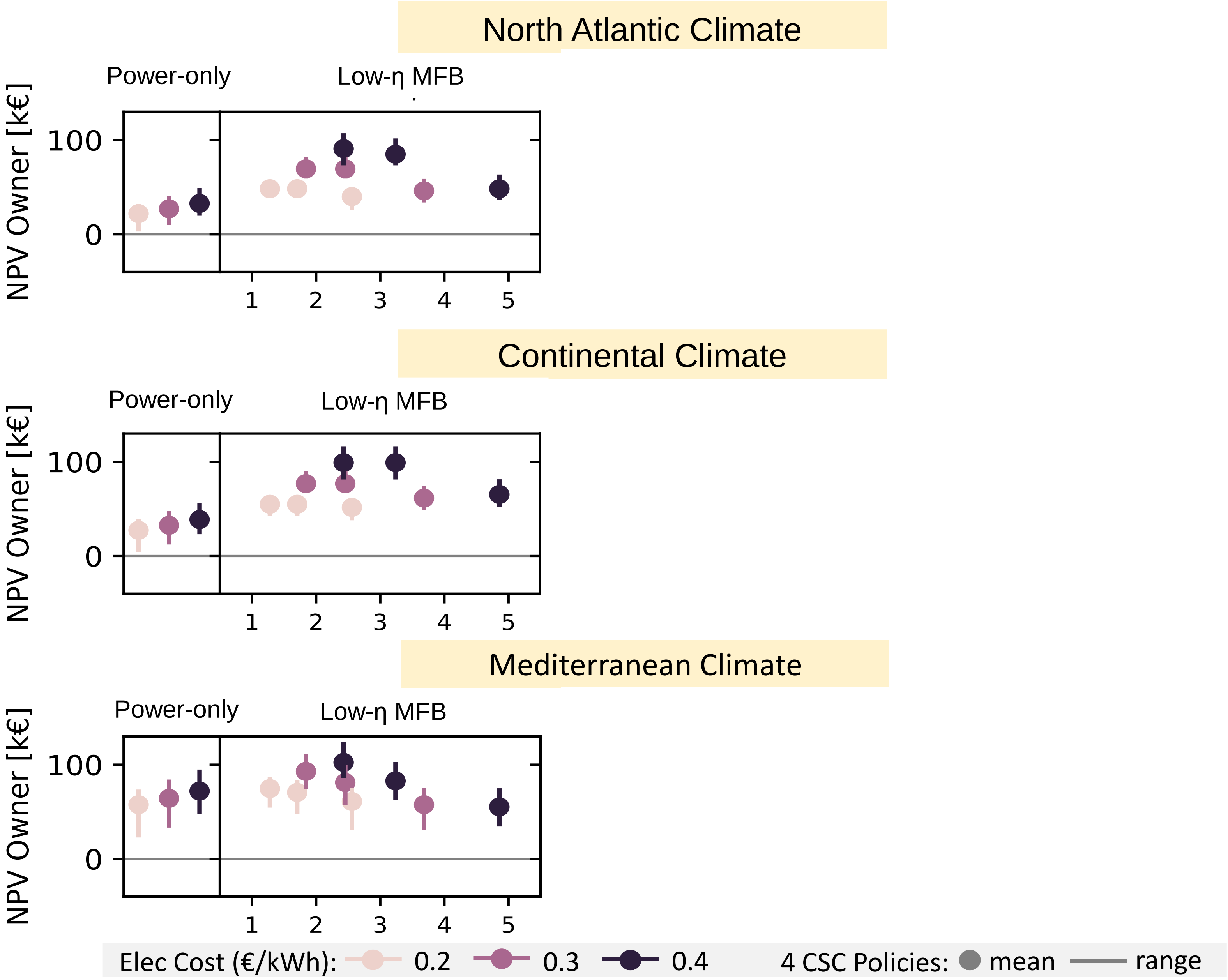
Elec Cost (€/kWh): 0.2 0.3 0.4 4 CSC Policies: mean range



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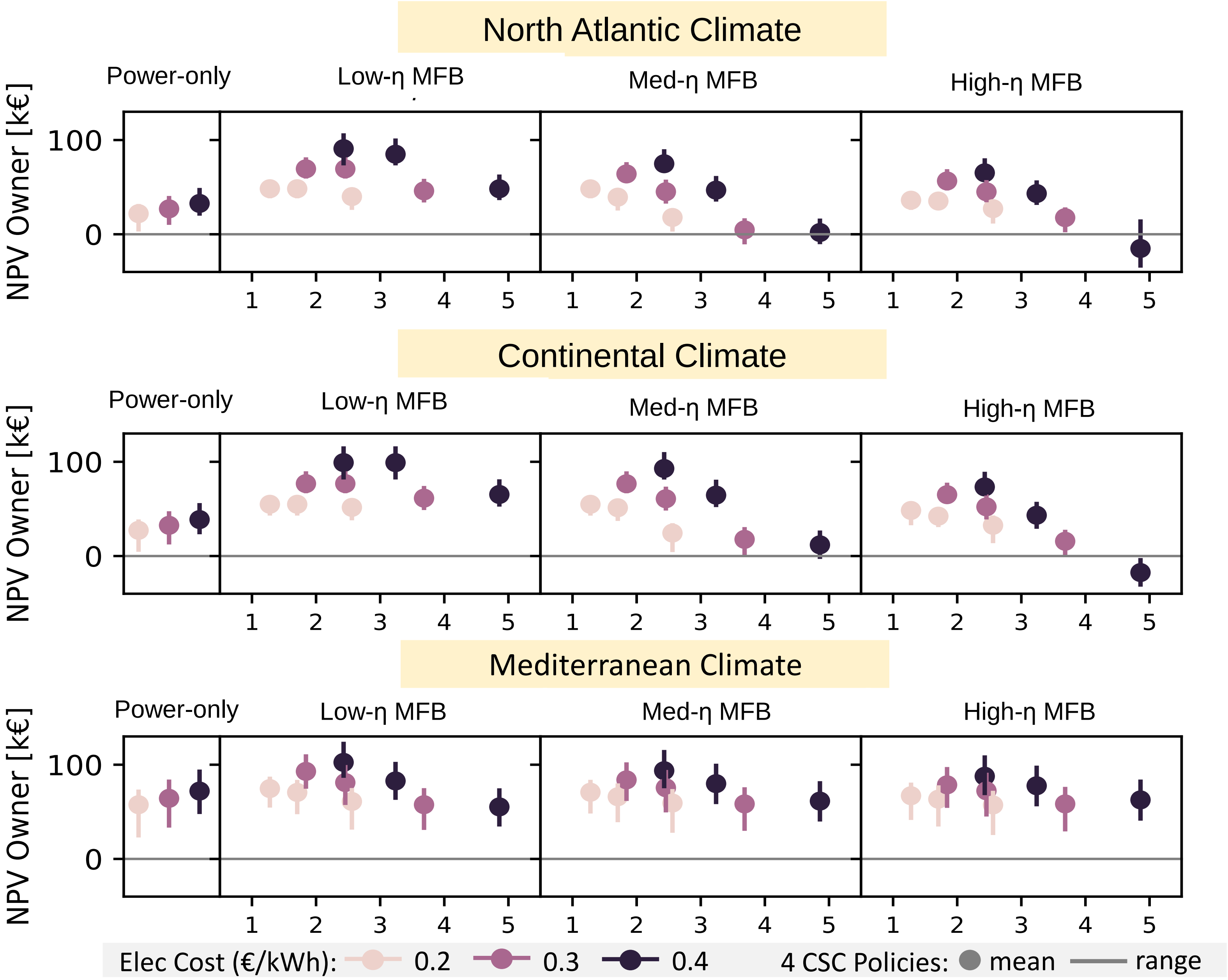

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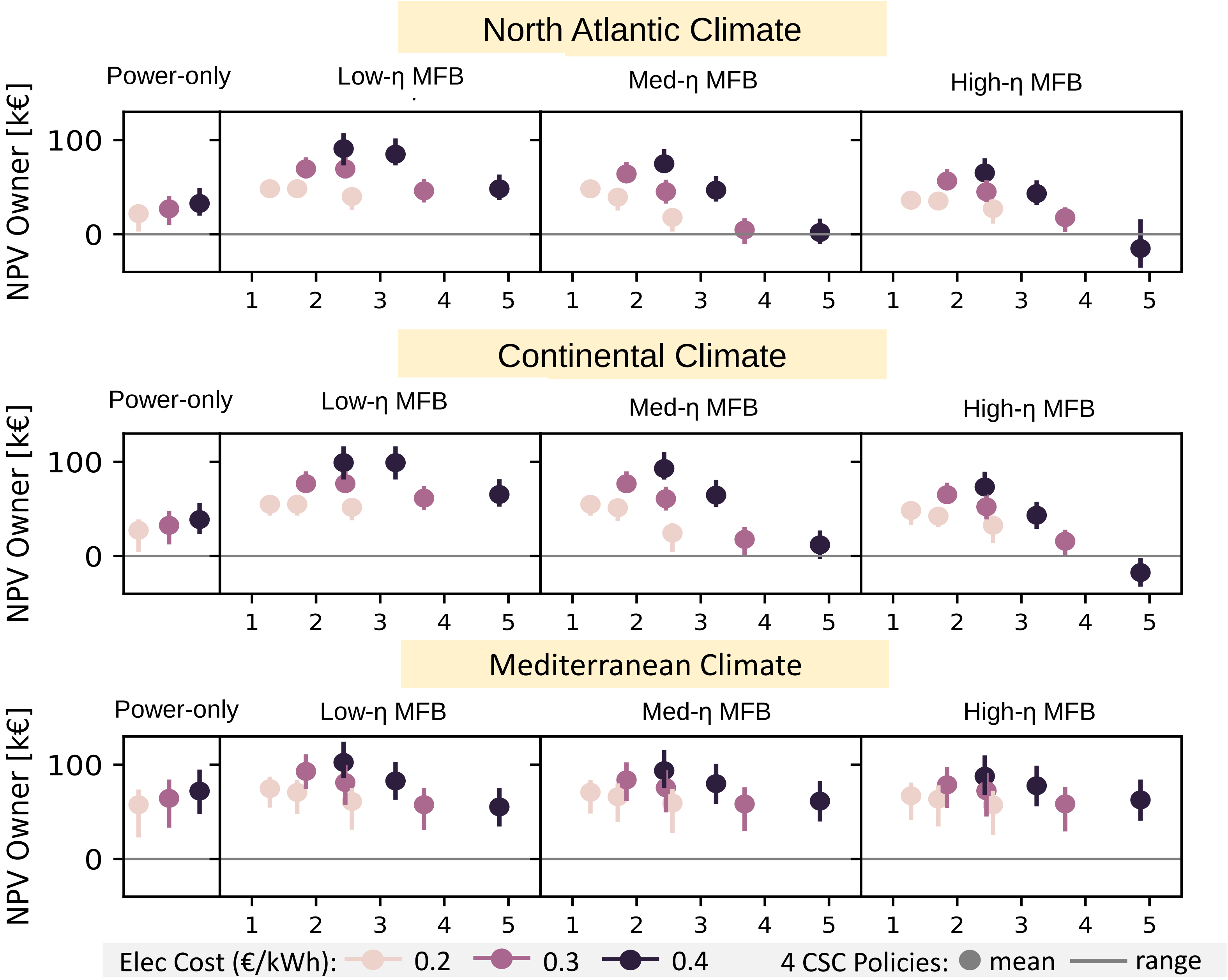
1. Residential demand side | 2. Research highlights | 3. Energy communities in European framework | 4. Take home messages



Key findings

<u>Negative NPV:</u>
↓ G + North Atl./Cont. + med-high η

<u>Split incentives:</u>
Low difference between power-only and power + heat in all climate zones

<u>Profitability Determinants:</u>
Highly case-specific

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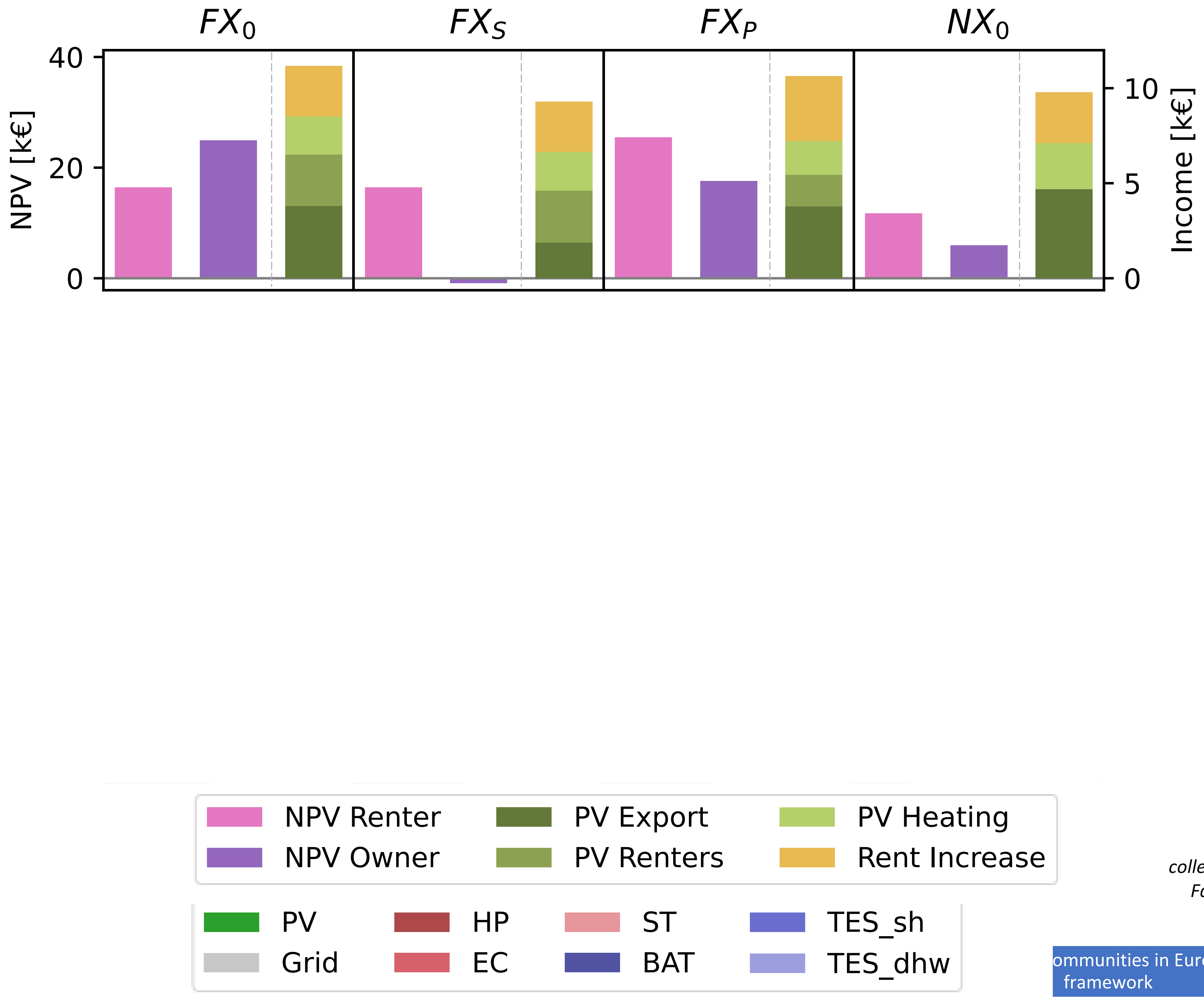

Munich case study

Key findings

- There is a large impact of CSC regulation on PV cash flows and operation and limited one low-carbon technology investment

- CSC frameworks combining grid tariff and tax exemptions and reduced internal prices for CSC electricity are the most beneficial for renters

- CSC frameworks combining grid tariff and tax exemptions and high surplus remuneration are the most beneficial for owners.

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3. Limitations and suggestions for further work

System impact	Include technical representation of the distribution grid + endogenous elec. prices
Electricity Loads	Consider individual profiles and load-shifting
Renovation measures	More granular passive retrofitting, renovation timing + heat distribution switch

3. Conclusions and policy recommendations

1. Under what climatic, techno-economic and regulatory conditions does CSC provide conjoint economic benefits for landlords and renters in MFBs?
2. How do different CSC regulations impact the distribution of benefits and low-carbon technology investment?

There is a large and varied impact of CSC regulation on PV cash flows and operation, and limited one on low-carbon technology investment

CSC in MFBs can provide conjoint benefits for building owners and renters across almost all of Europe → Focus on non-economic barriers

Split incentives in renter-occupied MFBs for decarbonizing heat in all European climates → Employ context-specific policy measures

CSC regulation -> low effect on investment
Large effect on distribution and operation → Focus on renter benefits and system impact

Agenda

1. Introduction and background on the residential demand side
2. Some research highlights to address key chellenges
    1. Understanding the demand side
    2. Demand side flexibility
    3. Low carbon technology applications and infrastructure
    4. Fully autonomous residential buildings
3. Case study: energy communities in different european frameworks
4. **Take home messages**

4. Take home messages

1. Buildings and decentralised/municipal energy systems are key to decarbonisation
2. Decentralized technology adoption changing temporal and spatial characteristics of demand
3. Challenge of interactions and complexity requires mixed methods approaches at multiple “levels”
4. Demand side / flexibility: empirical and simulative methods of households behaviour and demand
5. Low carbon technology applications and infrastructure: segmentation is key
6. Fully autonomous residential buildings: large technical and (with 50% cost increase) economic potential
7. Energy communities in different European frameworks:
    1. Regulation: mainly affects PV investment and cash flows
    2. Climate/buildings: crucial for the economics of heating in EC context

Prof. Dr. Russell McKenna

rmckenna@ethz.ch

Laboratory for Energy Systems Analysis

Paul Scherrer Institute

www.psi.ch/lea

https://www.linkedin.com/company/101087019/

ETH Zürich

Chair of Energy Systems Analysis

www.esa.ethz.ch

Thank you for your attention!