

# Overcoming the landlord–tenant dilemma: A techno-economic assessment of collective self-consumption for European multi-family buildings

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## ABSTRACT

Around half of the EU population lives in multi-family buildings, in which the landlord–tenant dilemma poses a significant barrier to low-carbon retrofits. Collective self-consumption (CSC) could present a promising way to overcome this barrier by creating mutual benefits for landlords and tenants. However, the techno-economic, climatic, and regulatory conditions for CSC show large variations in European countries, which raises the question how they will impact CSC benefits. In this study four different CSC regulations are integrated into a mixed-integer linear programming model, which determines the optimal retrofitting measures in a renter-occupied multi-family building under varying energy cost, climate, and envelope efficiency levels. The results show that CSC is beneficial for both landlords and tenants in all of Europe except for buildings in Western and Central Europe with an average U-value below 1.4 W/m<sup>2</sup>K and gas costs below 0.08 €/kWh. The findings also suggest that the landlord–tenant dilemma for decarbonizing heat persists in all European climates, pointing to the need for further support measures. In Southern Europe these could be provided in the form of more favorable CSC incentives for buildings with heat pumps, while in Central and Western Europe other measures, e.g. subsidies for heat pumps and renovation, are required.

## 1. Introduction

Buildings are responsible for 40% of the final energy consumption and 36% of the greenhouse gas emissions in the EU (European Commission, 2020). In order to decarbonize its building stock, the EU is aiming for 49% renewable energy consumption in buildings by 2030 (European Parliament and Council of the European Union, 2023) and is proposing to renovate the worst-performing 15% of its buildings (European Commission, 2021) by 2030. To deliver on these plans, the existing building stock must undergo extensive active retrofits with low-carbon technologies and passive retrofits on the building envelope. Roughly half of the EU population lives in multi-family buildings (MFBs) (Eurostat, 2023), which are predominantly renter-occupied in many Western European countries (Heiskanen and Matschoss, 2017). Despite their large retrofitting potential, MFB see very low levels of

low-carbon technology deployment in many jurisdictions (Fina et al., 2021).

A major barrier to realizing this potential are split incentives between landlords and tenants (Dato, 2018), also known as the landlord–tenant dilemma. Building owners are reluctant to invest in cost-efficient retrofitting measures, as they would have to pay for the initial investment, while renters would reap the benefits in the form of reduced energy bills. Apart from hindering decarbonization efforts, the landlord–tenant dilemma also leads to rental properties having lower energy efficiency ratings, leaving tenants more vulnerable to rising energy prices and energy poverty than homeowners (Lang et al., 2021). As outlined in the EU's Renovation Wave Strategy (European Commission, 2020), tackling energy poverty together with climate change through

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**Nomenclature****Abbreviations**

BAT	Battery
BAU	Business-as-usual
CF	Cash flow
CSC	Collective self-consumption
DHW	Domestic hot water
EE	Energy-efficiency-related
EH	Auxiliary electric heaters
FX	Full exemption
GB	Gas boiler
HP	Heat pump
Inv	Investment
MFB	Multi family building
NPV	Net-present value
O & M	Operation and maintenance
PV	Photovoltaics
PX	Partial exemption
RC	Resistance-capacitance
R0	No envelope renovation
R1	Envelope renovation with usual energy-efficiency measures
R2	Envelope renovation with advanced energy-efficiency measures
SCR	Self-consumption ratio
SH	Space heating
SSR	Self-sufficiency ratio
ST	Solar thermal
TES	Thermal energy storage

**Decision Variables**

Cap	Capacity solar conversion technologies (m <sup>2</sup> )
Cap	Capacity non-solar conversion technologies (kW)
Cap	Capacity storage technologies (kWh)
P	Energy flow (kWh)
R	Rent increase (€)
S	Storage level (kWh)
X	Retrofitting investment decision (Binary)

**Model Inputs**

A	Area (m <sup>2</sup> )
a	Heat pump model coefficients (–)
b	Heating curve coefficients (–)
C	Various costs (€)
Cap	Existing capacity or capacity limit solar technologies (m <sup>2</sup> )
Cap	Existing capacity or capacity limit non-solar technologies and electricity grid (kW)
Cap	Existing capacity or capacity limit storage technologies (kWh)
$c^{el/sh}$	Volumetric energy costs (€/kWh)
$c^{fix}$	Fixed retrofitting investment (€)
$c^{opex}$	Operation expenses factor (–)
$c^{var}$	Variable investment solar conversion technologies (€/m <sup>2</sup> )

$c^{var}$	Variable investment non-solar conversion technologies (€/kW)
$c^{var}$	Variable investment storage technologies (€/kWh)
$I$	Solar irradiance (kW/m <sup>2</sup> )
$L$	Lifetime (years)
$M$	Cash flow matrix (€/kWh)
$p$	Electricity prices (€/kWh)
$\dot{Q}$	Building heating and electricity loads (kW)
$S^0$	Initial state of charge of storage system (kWh)
$T$	Investment horizon (years)
$\Delta\tau$	Time step interval (1 h)
$\delta$	Charge–discharge factor (–)
$\eta$	Efficiency (–)
$\lambda$	Self-discharge losses (–)
$\rho$	Discount rate (–)
$\tau$	Electricity taxes and grid tariffs (€/kWh)

**Sets**

$d$	Demand types
$g$	Conversion technologies
$h$	Heating technologies
$i$	Conversion technologies, storage systems and electricity imports
$j$	Conversion technologies, storage systems, demand types and electricity exports
$k$	Storage systems
$r$	Passive retrofitting measures
$t$	Hourly timesteps
$x$	Conversion technologies and storage systems
$y$	Photovoltaic system and battery

**Indices**

bau	Business-as-usual
cd	Charge–discharge
dhw	Domestic hot water
el	Electricity
elxp	Electricity export
gtx	Grid tariff and electricity taxes (excl. VAT)
heat	Heating
in	Input energy carrier
max	Maximum
min	Minimum
out	Output energy carrier
own	Building owner
P	Pricing
rent	Renter
res	Residual value
rev	Reinvestment
S	Surplus
sh	Space heating
vat	Value added taxes
0	Reference

the renovation of worst-performing buildings and the use of low-carbon heating and cooling technologies should be considered a top priority for the European building sector.

Numerous policy solutions to the landlord–tenant dilemma have been described in the literature and implemented in European countries, such as informational tools, voluntary approaches, and financial incentives (Castellazzi et al., 2017). In this study we examine two financial incentives in detail, namely retrofitting fees and collective self-consumption (CSC), with particular focus placed on the latter. Retrofitting fees, also known as modernization levies, allow the building owner to raise the rent after performing active and passive retrofits that improve heating efficiency. The rent increase is often proportional to retrofitting investment or energy savings (Kühn et al., 2023). However, these two approaches, i.e. cost-based and energy-savings-based retrofitting fees, can place an additional financial burden on tenants as the rent increase is not compensated by lower energy bills (Kühn et al., 2023) thus leading to energy-related gentrification (März et al., 2022).

CSC initiatives, or “jointly-acting renewable self-consumers”, are defined in the recast of the Renewable Energy Directive (Directive (EU) 2018/2001) as a group of at least two final consumers who “generate renewable electricity for their own consumption, and who may store or sell self-generated renewable electricity”, and “who are located in the same building or multi-apartment block”. In the context of renter-occupied MFBs, CSC can create a win-win situation for both building owners and tenants for low-carbon technology retrofits. By investing in a photovoltaic (PV) system, building owners can benefit from additional income while renters can save on their electricity bills as they can often collectively self-consume PV electricity at a cost below grid electricity depending on the national CSC incentives. The availability of self-generated electricity from the PV system can also make it more attractive for the landlord to purchase a collective heat pump (HP), which is regarded as a promising solution to decarbonize buildings and reduce heating expenses for renters, especially when combined with passive retrofitting (International Energy Agency (IEA), 2022).

National CSC regulations around the world show a strong variation in the underlying economic incentives (Campos et al., 2020; Frieden et al., 2021; Jäger-Waldau et al., 2020). In particular, the differences in surplus remuneration, electricity taxes, and grid tariffs for self-generated electricity could have a large impact on the profitability of CSC projects (Fina et al., 2018; Scheller et al., 2018) and on their interaction with the grid and resulting costs/benefits for the wider system (Gunkel et al., 2023; Herencic et al., 2021). Moreover, there is large regional and national variation in climate, energy costs, and building stocks — factors that are also known to have a profound influence on the economic proposition of CSC (Canova et al., 2022; Fina et al., 2021; Braeuer et al., 2022).

These circumstances inevitably raise the question how different factors, such as CSC regulation, climate, energy costs, and building energy efficiency, will affect the economic viability of CSC in MFBs. The literature review in Section 2.2 reveals that a generalizable techno-economic assessment of CSC in MFBs accounting for all these factors and split incentives is still missing to the best of the authors’ knowledge. Such an assessment can provide researchers and policy makers with information regarding the strongest profitability determinants in various countries aiding in the design of country-specific support measures for CSC projects. In this study, therefore, the following research questions are posed:

- Under what conditions do CSC initiatives provide conjoint economic benefits for landlords and renters in MFBs?
- How do different CSC regulations impact the distribution of benefits and low-carbon technology investment?

To address these questions, a comparative analysis of the CSC regulatory frameworks for a selection of Western, Central and Southern European countries is performed, from which four CSC regulation variants are derived. The four CSC regulations along with an energy-cost-based retrofitting fee are integrated into a newly-developed MFB energy system optimization model, which considers active and passive

retrofitting measures. The model is applied to a MFB with varying climatic conditions, envelope efficiencies, and energy costs, where the CSC benefits for the renters and the building owner are computed under the four different CSC regulatory frameworks. Overall, this study contributes to the research body by:

- providing a generalizable techno-economic assessment of CSC;
- demonstrating that both landlords and tenants in MFBs can benefit from CSC across large parts of Europe;
- analyzing the determinants of CSC profitability and their case-specific degree of impact so that the most effective support measures for different contexts can be identified;
- identifying the CSC incentives that are most beneficial for individual CSC stakeholders.

The paper proceeds as follows. Section 2 provides an overview of the European regulatory landscape for CSC and summarizes the existing literature on the benefits and profitability determinants of CSC. Section 3 presents the optimization model including the mathematical formulation of owner and renter benefits. Section 4 describes the design of the European-wide analysis, which is performed with the optimization model. The results of the analysis are presented in Section 5 and discussed in Section 6, which includes a critical reflection on the employed methodology. Finally, in Section 7 a short summary and recommendations for policy makers and future work are given.

## 2. Background and literature review

### 2.1. CSC regulatory frameworks

The legal implementation of CSC in European countries shows large differences in terms of participation rules, governance structures, technical requirements, and economic incentives. For a comprehensive regulatory review of national CSC regulations considering all of these aspects the reader is referred to Campos et al. (2020) and Frieden et al. (2021). This review will discuss differences in economic incentives for CSC based on the national frameworks of the five most populous EU-28 countries – the United Kingdom, France, Germany, Italy, Spain – and Portugal, a country with a large solar potential. An overview is presented in Table 1. Economic incentives for CSC mainly comprise indirect support through exemption for volumetric grid tariffs and electricity taxes or direct support through volumetric subsidies and surplus remuneration schemes. Other forms of support such as income tax credits and PV investment subsidies are considered beyond the scope of this study. In terms of indirect support, almost all European countries exempt CSC operations in single MFBs from paying the volumetric grid tariff component, a notable exception is France (Lormeteau, 2022). In Spain this exemption is even extended for CSC using the public grid (Krug et al., 2023). In other countries, however, CSC schemes are only exempt from the grid tariff components for the unused voltage levels when sharing electricity through the public network, e.g. Portugal (Frieden et al., 2021), or are not allowed to use the public grid at all, e.g. Germany (Crowley-Nicol, 2020). Even more restrictive is the United Kingdom, where CSC is not legally recognized (Campos et al., 2020). For electricity taxes (excl. VAT), some countries allow full exemptions, such as Spain and Germany after the removal of self-consumption taxes in 2019 (Villalonga Palou et al., 2023) and 2023 (Bundestag, 2023), while others only exempt the part of the taxes related to financing renewable energy policies, e.g. Portugal (Frieden et al., 2021). Regarding direct support, few countries, e.g. Germany (Crowley-Nicol, 2020) and Italy (Canova et al., 2022), offer direct volumetric subsidies for CSC, while a wide range of different surplus remuneration exist, including fixed feed-in tariffs and market-based remuneration schemes (Campos et al., 2020).

For CSC projects where the owners of the distributed energy resource and consumers are not identical, e.g. landlords and tenants, an

**Table 1**

Economic incentives for CSC in MFBs in selected European countries: UK = United Kingdom, FR = France, DE = Germany, IT = Italy, ES = Spain, PT = Portugal.

	Elec. tax exemptions	Grid tariff exemptions	Volumetric subsidies	Surplus remuneration
UK <sup>a</sup>	–	–	–	Supplier-specific
FR	None	None or CSC-tariff	None	Fixed FiT or variable premium and guarantees of origin
DE	Full	Full	Yes	Fixed FiT or variable premium
IT <sup>b</sup>	None	Partial	Yes	Various mechanisms (incl. hourly zonal market price)
ES	Full	Full	None	Net billing at hourly market price - balancing costs
PT	Partial	Full	None	Monthly average market price

<sup>a</sup> No legal framework for CSC exists in the UK.<sup>b</sup> In the Italian CSC model, CSC electricity is first billed at retail prices and then volumetric grid fees are reimbursed and a 0.1 €/kWh subsidy is given.

internal selling price for CSC electricity must be agreed on. From the analyzed countries only in Germany is this price explicitly regulated. Namely, that the cost of CSC electricity for consumers, or tenants, can be at most 90% of the local cost of grid electricity (Crowley-Nicol, 2020). Other internal pricing mechanism have been proposed in the literature, such as marginal value pricing (Fleischhacker et al., 2019) or setting the price half way between the cost of grid electricity and the value of surplus (Mehta and Tiefenbeck, 2022; Belmar et al., 2023).

To summarize, there exist a wide variety of economic incentives for CSC in different European countries with full exemption of grid tariffs, partial–full exemptions of electricity taxes and different surplus remuneration schemes being the most widespread types, while internal pricing is generally not explicitly regulated.

## 2.2. Economic benefits of CSC and profitability determinants

Prior research indicates that CSC is profitable in many countries, e.g. Germany (Braeuer et al., 2022), Austria (Fina et al., 2021), Italy (Canova et al., 2022), Spain ((Gallego-Castillo et al., 2021); Villalonga Palou et al., 2023; Gil Mena et al., 2023), Portugal (Mansó Borràs et al., 2023; Belmar et al., 2023), and Australia (Roberts et al., 2022), with CSC only found to be unprofitable in France (Vernay et al., 2023). Existing studies have been mainly conducted on a national case study basis. An exception is Radl et al. (2020), who compared CSC at a neighborhood level in eight European countries in their analysis and find largely different economic benefits between them. However, they did not account for the split incentives between landlords and tenants and did not consider the effect of different national regulations for CSC.

While the literature agrees that CSC can provide positive economic benefits for its participants in many circumstances, several external factors have been found to influence the magnitude of achievable benefits, among them climatic conditions, energy costs, building types, low-carbon technology options, and CSC regulation as summarized in Table 2. In terms of climate effects, Fina et al. (2021) and Radl et al. (2020) determined up to a twofold increase of installed PV capacities and sixfold increase of benefits for CSC schemes (at the neighborhood and building level) in Southern Europe and New South Wales compared to Central and Western Europe. In addition, Radl et al. (2020) found that shared PV systems in Southern Europe are already profitable under market surplus remuneration, while in Central and Western Europe, additional savings through CSC are required to achieve positive benefits. For CSC initiatives in MFBs investing in PV and HP, Canova et al. (2022) observed exactly the opposite trend, namely up to a 150% higher net present value (NPV) in Northern versus Southern Italy.

Concerning the impact of energy costs, multiple studies have identified a strong positive dependency of the profitability of CSC-oriented PV systems on the local cost of electricity (Radl et al., 2020; Fina et al., 2018; Gallego-Castillo et al., 2021). Conversely, when considering CSC projects with PV and HP, Fina et al. (2019) found for the Austrian case that increasing electricity prices by 2% per year lead to a 20% reduction of NPV as the increased cost savings for PV are outweighed by the reduced cost savings for HP.

Regarding the impact of building energy efficiency, Braeuer et al. (2022) reported 60% higher CSC benefits for building owners of pre-1980 versus post-2000 German MFB. They found that the lower envelope efficiency of the older building leads to increased sales of self-generated energy for heating. However, the authors did not consider passive retrofitting and subsequent rent increases as additional revenue stream for the landlord.

The economic impact of adding more low-carbon technologies to a CSC project is not definitive according to the current state of the art. For instance when installing HP in MFBs in addition to PV, Canova et al. (2022) determined up to 10 pp increase in the rate of return of the CSC project in Northern Italy while it stayed the same or even decreased by up to 2 pp in Southern Italy. Similarly, for CSC projects in Germany and Austria purchasing a PV and HP yields lower benefits than installing PV and new gas boiler (GB) (Braeuer et al., 2022; Fina et al., 2019). The investments into HP often have to be accompanied by passive retrofits in order to achieve cost-efficient HP operation in buildings with high heat demands. Previous findings indicate, however, that passive retrofitting in MFBs is either unprofitable for all measures (Fina et al., 2019; Wu et al., 2017) or only profitable for partial measures (Garavaso et al., 2021; Niemelä et al., 2017; Ferrara et al., 2019) thus further negatively affecting the achievable benefits in CSC operations with HP.

Several studies have also examined the impact of regulatory frameworks on the profitability of CSC. Volumetric subsidies and tax and grid tariff exemptions have been identified as ways to increase installed PV capacities and CSC benefits at building (Braeuer et al., 2022; Garavaso et al., 2021; Pinto et al., 2020) and neighborhood (Herencic et al., 2021) scales. Gallego-Castillo et al. (2021) determined the same effects for higher surplus remuneration while also reporting a reduced likelihood of battery investment. The impact of different CSC electricity pricing models has been explored by Fleischhacker et al. (2019), who determined that different pricing models only redistribute benefits between CSC technology owners and consumers without affecting total welfare of the MFB.

The sources considered in the foregoing discussion are summarized in Table 3. They show that CSC projects are largely profitable but that the magnitude of economic benefits is strongly dependent on external factors, such as climate, energy costs, building energy efficiency, technology options, and CSC incentives. These factors, however, have mainly been taken into account individually as local sensitivities in national contexts. Based on this review, we conclude that an economic assessment of CSC initiatives under split incentives considering the European diversity in climatic, techno-economic and regulatory conditions is missing.

## 3. Building energy system optimization model

Section 3.1 provides an overview of the available retrofitting options in the optimization model. Section 3.2 introduces the objective function of the model, i.e. the NPV of the building owner. Section 3.3 shows how the energy-cost-based retrofitting fee is represented in the model and how other key performance indicators, e.g. NPV of the renters, are recorded. The implementation of the CSC regulatory frameworks and the technical constraints in the optimization model are presented in Appendices B.1 and B.2. The corresponding data used in the optimization model is provided in Section 4 and Appendix A.

**Table 2**

Profitability determinants and their economic effect on CSC projects.

Key findings	Studies
<i>Climate:</i> PV → higher benefits with higher irradiance; PV+HP → higher benefits with colder climates	Gallego-Castillo et al. (2021), Fina et al. (2021), Radl et al. (2020) and Canova et al. (2022)
<i>Energy costs:</i> PV → higher benefits with higher electricity costs; PV+HP → higher benefits with lower electricity costs	Fina et al. (2019, 2021), Radl et al. (2020) and Villalonga Palou et al. (2023)
<i>Building energy efficiency:</i> higher benefits for lower envelope efficiency	Braeuer et al. (2022)
<i>Technology options:</i> adding HP increases CSC returns in Northern Italy but not in the Southern Italy; PV+HP not cost-effective versus PV+GB in Germany; passive retrofit generally not cost-effective	Braeuer et al. (2022), Fina et al. (2019), Canova et al. (2022), Wu et al. (2017), Niemelä et al. (2017) and Ferrara et al. (2019)
<i>CSC regulation:</i> Higher benefits for increased surplus remuneration and grid tariff and tax exemptions; redistribution of benefits for different internal pricing schemes	Gallego-Castillo et al. (2021), Garavaso et al. (2021), Herencic et al. (2021), Braeuer et al. (2022) and Fleischhacker et al. (2019)

**Table 3**

Overview of selected papers relevant to the current study.

Author	Country <sup>a</sup>	Spatial level <sup>b</sup>	CSC regulation		Sensitivities <sup>d</sup>				Model features <sup>e</sup>		
			Exemptions <sup>c</sup>	Surplus Remun.	CL	EC	BE	RF	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

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

### 3.1. Model structure

In this study we develop a mixed-integer linear programming model to analyze the economic benefits and low-carbon technology investment under different CSC regulatory frameworks in a renter-occupied MFB. The model determines the active and passive retrofit technologies and the operation of the resulting building energy system that maximize the NPV of the primary investor, i.e. the building owner, in the CSC project. At the same time the model guarantees savings for the renters compared to a pre-computed business as usual (BAU) case.

The model has two options for low-carbon technologies. In the first one, which is displayed in Fig. 1 and referred to as “CSC with heat” from here on, the model can choose to install the following conversion and storage technologies to satisfy the electric and thermal loads of the renters in the MFB:

- Solar photovoltaics (PV) and solar thermal (ST)
- Air-source heat pumps (HP)
- Auxiliary electric heater (EH)
- Batteries (BAT)

- Thermal energy storage for space heating (sh) ( $TES_{sh}$ )
- Thermal energy storage for domestic hot water (dhw) ( $TES_{dhw}$ )

In addition, the following three different building envelope renovation levels are included as passive retrofitting options:

- No envelope renovation (R0)
- Envelope renovation with usual energy-efficiency measures (R1)
- Envelope renovation with advanced energy-efficiency measures (R2)

In the second option, “CSC no heat”, only PV and BAT are available as low-carbon technologies and no retrofit investments on the heat supply and demand side, i.e. passive retrofitting, are made.

### 3.2. Objective function

The model maximizes the NPV of the building owner  $NPV^{own}$  (€), which is calculated as the sum of investment and discounted annual cash flows over the investment period  $T$  (years) as shown in Eq. (1). In



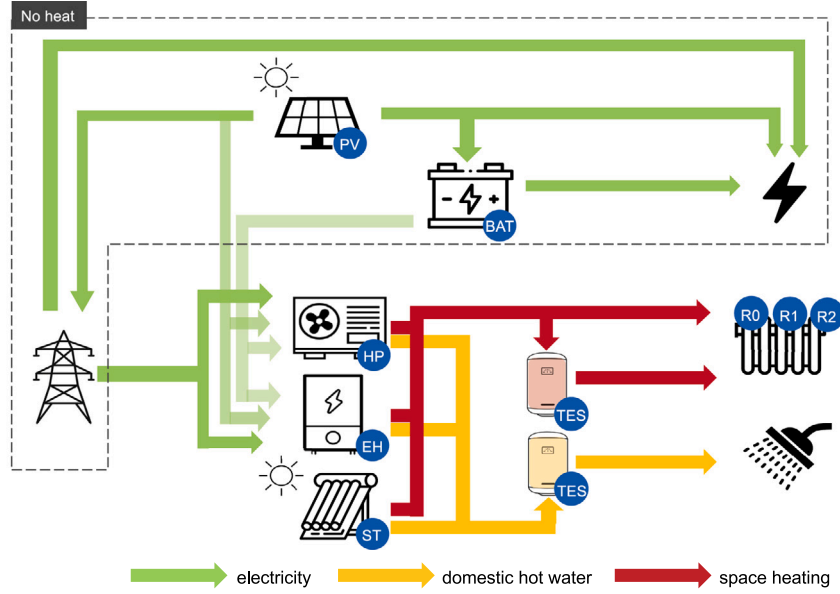


Fig. 1. Optimization model architecture for CSC no heat and CSC with heat showing all possible energy flows, energy conversion and storage technologies and passive retrofitting measures. PV = photovoltaics, BAT = battery, HP = heat pump, EH = electric heater, ST = solar thermal, TES = thermal energy storage, R0,R1,R2 = building envelope retrofit levels.

terms of nomenclature it is noted that bold symbols represent decision variables, while all non-bold symbols represent model parameters.

$$\max. \quad NPV^{own} = -Inv + \sum_{n=1}^T \frac{CF}{(1+\rho)^n} \quad (1)$$

Total investment is split into investment for active and passive retrofitting measures as presented in Eq. (2).

$$Inv = \underbrace{\sum_{x \in \{g \cup k\}} \mathbf{X}_x \cdot c_x^{fix} + \mathbf{Cap}_x \cdot c_x^{var} \cdot \left(1 + \frac{X_x^{rev}}{(1+\rho)^{L_x}} - \frac{L_x^{res}}{L_x} \cdot \frac{1}{(1+\rho)^T}\right)}_{\text{Active Retrofitting Investment}} + \underbrace{\sum_r \mathbf{X}_r \cdot c_r^{fix,full} \cdot \left(1 + \frac{X_r^{rev}}{(1+\rho)^{L_r}} - \frac{L_r^{res}}{L_r} \cdot \frac{1}{(1+\rho)^T}\right)}_{\text{Passive Retrofitting Investment}} \quad (2)$$

In terms of active retrofitting investment, the assumption is made that every conversion or storage technology must be bought new and that only the heat distribution system is reused. The investment for every active retrofitting measure  $x$  consists of a fixed  $c_x^{fix}$  (€) and capacity-dependent component  $c_x^{var}$  (€/m<sup>2</sup>, €/kW or €/kWh). Each active retrofitting measure is described by a binary variable  $\mathbf{X}_x$ , which equals 1 if it is purchased, and a continuous variable  $\mathbf{Cap}_x$ , which describes its installed capacity in terms of panel area (m<sup>2</sup>) for the PV and ST system, nominal thermal power (kW) for other conversion technologies and maximum energy content (kWh) for all storage systems. The investment for every passive retrofitting measure  $r$  is represented by a binary variable  $\mathbf{X}_r$  multiplied by a lump-sum  $c_r^{fix,full}$ , which represents the full cost of renovating the building envelope, i.e. “visual” refurbishment and energy efficiency upgrades. The model accounts for reinvestment and residual value next to initial investment, so that retrofitting measures with different lifetimes  $L_{x/r}$  can be considered. Reinvestment is necessary for measures where  $L_{x/r}$  is smaller than the investment horizon  $T$ . In these cases the measure is purchased again at the end of its lifetime  $L_{x/r}$  and the binary  $X_{x/r}^{rev}$  is set to one. Residual value is accounted for when a (re)invested measure has not reached its full lifetime at end of the investment horizon. In these cases the residual lifetime  $L_{x/r}^{res}$  of the measure will be greater than zero. Value

is assumed to depreciate linearly. Both residual value and reinvestment are discounted at a rate  $\rho$  (%).

The cash flows of the building owner are computed for one year as shown in Eq. (3).

$$CF = \underbrace{\sum_{i,j,t} \mathbf{P}_{i,j,t} \cdot M_{i,j,t}^{own}}_{\text{PV Revenues}} + \underbrace{\mathbf{R}}_{\text{Rent Increase}} - \underbrace{\sum_{y \in \{PV,BAT\}} (\mathbf{Cap}_y \cdot c_y^{var} + \mathbf{X}_y \cdot c_y^{fix}) \cdot c_y^{opex}}_{\text{PV/BAT O\&M Costs}} \quad (3)$$

Positive annual cash flows can be gained through the operation of the PV system or by increasing the annual rent. The latter allows the building owner to increase the rent by  $\mathbf{R}$  (€) in order to recuperate investments into heating system or building envelope upgrades and will be explained in more detail in the following section. The former is calculated as the annual sum of all energy flows  $\mathbf{P}_{i,j,t}$  multiplied by their associated volumetric revenues for the building owner  $M_{i,j,t}^{own}$ , which depend on the specific CSC regulatory framework. To accurately represent their intricacies,  $M_{i,j,t}$  and  $\mathbf{P}_{i,j,t}$  are defined using three indices. The first index  $i$  designates the departure node of the energy flow, while the second  $j$  specifies its destination node. Both together allow the conversion and storage technologies in the building to be described using multiple inputs and outputs. The third index indicates the hourly time step  $t$ . For example,  $\mathbf{P}_{PV,HP,3}$  designates the energy flow from the PV system to the HP at time step 3 and  $M_{PV,HP,3}^{own}$  designates the corresponding cash flow the owner receives per kWh of  $\mathbf{P}_{PV,HP,3}$ .

Negative annual cash flows are incurred by the operation and maintenance (O&M) of the conversion and storage technologies. The O&M costs are modeled as a fixed percentage  $c^{opex}$  (%) of their individual nominal investment. Only the O&M costs for the PV and BAT system are included in the objective function, as the O&M costs for the heating system are passed onto the renters.

### 3.3. Energy-cost-based retrofitting fee and key performance indicators

Just as CSC frameworks provide incentives for building owners to invest in PV systems, corresponding support is required to provide incentives for heating upgrades in renter-occupied buildings. Such an

incentive is implemented in the model in the form of an energy-cost-based retrofitting fee in the Eqs. (4) and (5). To recuperate investments into heat supply and storage systems  $h$  and building envelope upgrades  $r$ , the building owner can increase the annual rent by up to 8%<sup>1</sup> of the nominal value of these investments as shown in Eq. (4). However, for passive retrofitting, only the energy-efficiency-related renovation costs  $c_r^{fix,EE}$  are considered in the rent increase.

$$R \leq 0.08 \cdot \left( \sum_h \text{Cap}_h \cdot c_h^{var} + \sum_h X_h \cdot c_h^{fix} + \sum_r X_r \cdot c_r^{fix,EE} \right) \quad (4)$$

An additional constraint (5) guarantees that the owner invests in heating retrofits with corresponding rent increases that are compensated by lower energy bills for tenants. It does so by ensuring that the sum of rental fees and heating expenses remain at least 10%<sup>2</sup> lower than in the BAU case for the renters.

$$R + C_{new}^{heat} \leq 0.9 \cdot C_{bau}^{heat} \quad (5)$$

The renters' heating expenses in the CSC project  $C_{new}^{heat}$  (€) and in the BAU case  $C_{bau}^{heat}$  (€) are calculated as the sum of annual fuel and O&M costs. In the CSC project, the fuel costs are calculated as the sum of all energy inputs  $P_{i,h,t}$  to heating technologies  $h$  times their corresponding volumetric cost for renters  $M_{i,h,t}^{rent}$  as shown in Eq. (6).

$$C_{new}^{heat} = \underbrace{\sum_{i,h,t} P_{i,h,t} \cdot M_{i,h,t}^{rent}}_{\text{CSC project heating electricity costs}} + \underbrace{\sum_h (\text{Cap}_h \cdot c_h^{var} + X_h \cdot c_h^{fix}) \cdot c_h^{opex}}_{\text{CSC project heating O\&M costs}} \quad (6)$$

In the BAU case, the fuel costs are calculated as the product of the BAU total heat demand  $\dot{Q}_{bau,t}^{sh} + \dot{Q}_{bau,t}^{dhw}$  (kW) times the time interval  $\Delta\tau$  (h) and the BAU volumetric cost for heating  $c_{bau}^{sh}$  (€/kWh) divided by the efficiency of the BAU heating technology  $\eta_{bau}^{sh}$  as detailed in Eq. (7). The heat load is assumed to be supplied without the use of a TES system. For both  $C_{new}^{heat}$  and  $C_{bau}^{heat}$ , the O&M costs are calculated as a fixed percentage  $c^{opex}$  of the nominal investment into heat supply and storage systems. For the BAU case, this investment comprises the fixed investment for the existing heating system  $c_{bau}^{fix}$  (€) and the variable investment  $c_{bau}^{var}$  (€/kW) multiplied by its thermal capacity of  $\text{Cap}_{bau}$  (kW).

$$C_{bau}^{heat} = \underbrace{(\dot{Q}_{bau,t}^{sh} + \dot{Q}_{bau,t}^{dhw}) \cdot \Delta\tau \cdot \frac{c_{bau}^{sh}}{\eta_{bau}^{sh}}}_{\text{BAU heating fuel costs}} + \underbrace{(\text{Cap}_{bau} \cdot c_{bau}^{var} + c_{bau}^{fix}) \cdot c_{bau}^{opex}}_{\text{BAU heating O\&M costs}} \quad (7)$$

Additionally, in the BAU case, the building's electricity load  $\dot{Q}_{bau,t}^{el}$  (kW) is entirely covered by grid electricity imports. This means that no CSC takes place and all renters pay their electricity bills individually.

Considering the above assumptions, the formation of a CSC initiative leads to a total net present value for the renters of  $NPV^{rent}$  compared to the BAU case. This value is recorded in the model as shown in Eqs. (8) and (9) and does not directly constrain the objective function. Together with  $NPV^{own}$ ,  $NPV^{rent}$  (€) is used to capture how different CSC regulations affect the distribution of benefits.

No heat:

$$NPV^{rent} = \sum_{n=1}^T \frac{1}{(1+\rho)^n} \cdot \left( \underbrace{\sum_t \dot{Q}_{bau,t}^{el} \cdot \Delta\tau \cdot c_{bau,t}^{el}}_{\text{BAU elec. costs}} - \underbrace{\sum_{i,j,t} P_{i,j,t} \cdot M_{i,j,t}^{rent}}_{\text{CSC project elec. costs}} \right) \quad (8)$$

With heat:

$$NPV^{rent} = \sum_{n=1}^T \frac{1}{(1+\rho)^n} \cdot \left( \underbrace{\sum_t \dot{Q}_{bau,t}^{el} \cdot \Delta\tau \cdot c_{bau,t}^{el}}_{\text{BAU elec. costs}} - \underbrace{\sum_{i,j,t} P_{i,j,t} \cdot M_{i,j,t}^{rent}}_{\text{CSC project elec. costs}} + C_{bau}^{heat} - \underbrace{\sum_h (\text{Cap}_h \cdot c_h^{var} + X_h \cdot c_h^{fix}) \cdot c_h^{opex}}_{\text{CSC project heating O\&M costs}} - R \right) \quad (9)$$

Additionally, to capture interactions with the grid, self-consumption and self-sufficiency ratios, SCR and SSR, are recorded as shown in Eqs. (10) and (11), where  $P_{PV,exp,t}$  represents electricity exports.

$$SCR = \sum_t \frac{\underbrace{(\sum_j P_{PV,j,t}) - P_{PV,exp,t}}_{\text{Self-consumed electricity}}}{\underbrace{\sum_j P_{PV,j,t}}_{\text{PV production}}} \quad (10)$$

$$SSR = \sum_t \frac{\underbrace{(\sum_j P_{PV,j,t}) - P_{PV,exp,t}}_{\text{Self-consumed electricity}}}{\underbrace{(\sum_j P_{PV,j,t} + P_{el,j,t}) - P_{PV,exp,t}}_{\text{Total electricity consumption}}} \quad (11)$$

### 3.4. Technical constraints

The design, sizing, and operation of the building energy technologies has to guarantee the supply of the MFB's electrical and thermal demands while complying with multiple technical constraints. These include energy balances for the conversion technology, storage system, and demand nodes and general technical constraints imposed by the building and its energy systems, e.g. capacity limits, as presented in Appendix B.2.

## 4. European-wide study design

This study analyzes the economic feasibility of forming CSC initiatives in renter-occupied MFBs across Europe. In order to capture as much variation between European countries as possible, the optimization model is applied to an archetypical MFB, which is translated into a broad range of climate zones, envelope efficiency, and electricity and gas cost levels. For each of these four factors three values are considered, as shown in Table 4, resulting in 81 combinations. For each combination, heating and electricity costs are computed for the BAU case, which comprises the operation of the unrenovated MFB (R0) with a gas boiler and without local electricity generation. Then for each of the 81 BAU cases the net benefits of forming a CSC initiative are computed in the optimization model as described in Section 3. This step is performed for two different low-carbon technology options, CSC heat and CSC no heat, and four different CSC regulatory frameworks resulting in 648 scenarios in total. The optimization model, however, is only run 432 times as the variation in gas cost does not affect the CSC no heat cases. The data for energy supply, i.e. technologies and prices, and energy demand of the MFB are given for the BAU case in Section 4.1 and for the CSC initiative in Section 4.2 and Appendix A.

### 4.1. BAU case

#### 4.1.1. BAU energy supply

The BAU building features a condensing gas boiler for SH and DHW to reflect the 43% share of natural gas in final energy consumption for residential heating in the EU-28 (Bertelsen and Mathiesen, 2020). The heating system is assumed to be installed in a collective configuration,

<sup>1</sup> This value is based on the German BGB §559 law.

<sup>2</sup> Currently, there is no national regulation regarding energy-cost-based retrofitting fees for heating. Therefore, we reference the German CSC regulation, which mandates at least 10% savings on CSC electricity for the renters compared to BAU (cf. Section 2.1).

**Table 4**

Scenario-dependent optimization model input parameters. Grey parameters affect the BAU case, green ones affect the CSC project and white parameters affect both BAU and CSC.

Parameter family	Subparameter	Values
Gas costs ( $\eta_{bau}^{sh}$ )		0.08/0.12/0.16 [€/kWh]
Regulated electricity cost component ( $\tau^{gtx}$ )		0.06/0.14/0.22 [€/kWh]; Leads to average $c_{bau}^{el}$ of 0.21/0.30/0.39 [€/kWh]
Initial envelope efficiency (R0)	U-values	low/med/high $\hat{=}$ average U-value 2.4/1.4/0.75 [W/m <sup>2</sup> K] (cf. Table A.8)
Climate zone	Weather data	London/Munich/Lisbon 2019
	Electricity price shape	UK/DE/PT 2019 day-ahead price
	Occupancy profiles	UK/DE/ES time use survey data
CSC regulation ( $M_{i,j,t}$ )		Four variants (cf. Table 6)
CSC available technologies		No heat: PV, BAT, R0
		With heat: PV, BAT, HP, EH, ST, TES, R0, R1, R2

**Table 5**

Cost of electricity components for the renters in the BAU case and the electric heating systems for CSC. Values are in cent/kWh.

Electricity cost components	BAU	HP/EH
Average electricity price ( $\bar{p}^{el}$ )	12.1	12.1
Regulated component ( $\tau^{gtx}$ )	6/14/22	2/10/18
VAT ( $\tau^{vat}$ )	15%	15%
Average electricity cost ( $\bar{c}^{el}$ )	20.8/30.0/39.2	16.2/25.4/34.6

i.e. one central unit per MFB, and to operate at an efficiency  $\eta_{bau}^{sh}$  of 0.9 (EnergieSchweiz, 2015). The O&M costs for the heating system – paid by the renters as mentioned in Section 3.2 – are detailed in Appendix A. The fuel cost for the gas boiler  $c_{bau}^{sh}$  is assumed to be 0.08, 0.12 or 0.16 €/kWh depending on the BAU case. In addition, each apartment unit is assumed to have a split air conditioning system for space cooling operating with a temperature-dependent efficiency (Ryu et al., 2013) at a cost of  $c_{bau,t}^{el}$  as detailed below.

In terms of electricity supply, renters purchase their electricity individually at a case-specific cost of  $c_{bau,t}^{el}$ , and no electricity generation technologies are present in the building. The mean of  $c_{bau,t}^{el}$  depends on the electricity cost level and its shape on the climate zone, which represent the three largest climatic regions in Europe based on the Köppen classification (Beck et al., 2018), i.e. the Cfb, Dfb, and Csa zones. In this study they are referred to as North Atlantic, Continental, and Mediterranean climates respectively with the corresponding climate-specific data taken for the cities of London, Munich, and Lisbon.  $c_{bau,t}^{el}$  is composed of a dynamic electricity price  $p_t^{el}$  along with static regulated tariff components  $\tau^{gtx}$ , i.e. network costs, taxes (excl. VAT), and levies, which are both subject to a VAT rate  $\tau^{vat}$  of 15%. The electricity price  $p_t^{el}$  is either set to the 2019 hourly day-ahead price for Germany, Portugal, or the UK depending on the climate zone and then rescaled to an average  $\bar{p}^{el}$  of 0.121 €/kWh. This value corresponds to the current (02 Nov 2023) price for German base load futures for 2025 and allows expectations about future price developments to be factored in. The regulated tariff components for renters  $\tau_{bau}^{gtx}$  are set to values of 0.06, 0.14, 0.22 €/kWh depending on the electricity cost level. The wide ranges are chosen to capture the large spread in electricity tax levels (and network costs to a lesser extent) across European countries. The resulting electricity costs are shown in Table 5.

#### 4.1.2. BAU energy demand

The DHW load profile is climate-dependent and created according to the method detailed in Pezzutto et al. (2019) assuming an annual consumption of 32.5 kWh/m<sup>2</sup>/year.

The space heating and cooling demand profiles are dependent on the climate zone and on the envelope efficiency and are determined

using the resistance capacitance (RC) building model from Schütz et al. (2017). The model has to be fed with the geometric and thermal properties of the building envelope as well as ambient temperature and solar irradiance data and a lower and upper temperature comfort limit. The geometric properties of the MFB are based on Tabula's "DE.N.MFH.06.Gen" reference building representing the typical German MFB built between 1969–1978 (Loga et al., 2016). The building consists of 8 dwellings with a combined heated floor area  $A_f$  of 469 m<sup>2</sup> and a roof area  $A_{roof}$  of 217 m<sup>2</sup>. In some European countries MFB archetypes feature more dwellings, e.g. Poland, Portugal, Czech Republic (ENTRANZE, 2014). In this case the MFB chosen in this study can be seen as a worst case in terms of scale effects (McKenna et al., 2017). The thermal properties of the MFB, i.e. U-values, depend on the case-specific envelope efficiency as shown in Table A.8. In the BAU case, the building is assumed to be in the unrenovated state (R0). The chosen range of U-values for R0 captures 80%<sup>3</sup> of the floor area of MFBs built up to 1990 in Europe. The outdoor temperature  $T_t^e$  and solar irradiance data  $I_t$  for the three climate zones are taken from European Commission Joint Research Centre (2022) for London, Munich, and Lisbon in 2019 with the solar panel set at the optimal slope and azimuth angle. The lower and upper comfort limits are set to 20 °C and 27 °C. Using the above inputs, the space heating and cooling profiles are pre-computed for every envelope efficiency and climate combination.

The electricity load profiles reflect demand for lighting, appliances and cooling. Lighting and appliance profiles are generated with the CREST demand model (Richardson et al., 2010) considering local occupancy profiles and lighting consumption and correspond to an average annual consumption of 2500 kWh per dwelling. The electricity demand for cooling is obtained by weighting the thermal cooling load from the RC model with the air conditioning efficiency mentioned in Section 4.1.1.

#### 4.2. CSC with low-carbon energy systems

##### 4.2.1. CSC energy supply

In the CSC with heat option, the existing building energy systems have to be replaced with the low-carbon options shown in Table A.7. In the CSC no heat option, the gas boiler is kept for heating and only PV panels and batteries are available as low-carbon technologies.

Compared to the BAU case, the electricity costs for the renters are reduced — to which extent depends on the chosen CSC framework, which will be explained in the following. As noted in Section 2.1, full exemptions of grid tariffs combined with partial or full exemptions of levies and taxes (excl. VAT) for shared PV electricity are one of

<sup>3</sup> own calculation with data from Jankovic et al. (2021).



**Table 6**

Four CSC regulation variants exploring the impact of different surplus remuneration levels, CSC pricing models, and tax and grid tariff exemptions. FX = full exemption, NX = no exemption, 0 = reference, S = reduced surplus remuneration, P = lower selling price for CSC electricity.

CSC regulation variants	$\tau^{gtx}$ exemption	Internal pricing	Surplus remuneration
Reference ( $FX_0$ )	100%	$0.9 \cdot c_{bau,t}^{el}$	$p^{el}$
Lower surplus value ( $FX_S$ )	100%	$0.9 \cdot c_{bau,t}^{el}$	$0.5 \cdot p^{el}$
Lower internal pricing ( $FX_P$ )	100%	$0.5 \cdot (c_{bau,t}^{el} + p^{el})$	$p^{el}$
No exemptions ( $NX_0$ )	0%	$0.9 \cdot c_{bau,t}^{el}$	$p^{el}$

the most widespread incentives for CSC in single MFBs. However, the maximum price that landlords can charge renters for PV electricity is often not explicitly regulated and there exist varying levels of surplus remuneration across different European countries. Therefore, the first three regulation variants  $FX_0$ ,  $FX_P$  and  $FX_S$  explore the effects of different pricing models and surplus remuneration levels while considering full exemptions (FX) of both grid tariff and taxes. The fourth one,  $NX_0$ , represents the case in which no exemptions (NX) are provided for grid tariffs and taxes for CSC in a single MFB.

The differences between the CSC regulation variants are presented in Table 6 and their detailed mathematical representation in the optimization model is shown in Appendix B.1. In addition, it is assumed for all four regulations that PV electricity used in the HP or EH is sold to the renters at the same price as CSC electricity. This sale is fully exempt from grid tariff and taxes as it is considered as self-consumption. For the electricity imports from the grid, we assume that the renters pay their bills individually at their previous rate  $c_{bau,t}^{el}$ , while imports to the HP and EH are charged at a reduced price  $c_{HP}^{el}$  (cf. Table 5) as a result of the higher annual consumption. All annual cash flows and savings achieved under the different CSC regulations are discounted at a rate  $\rho$  of 4% over an investment horizon  $T$  of 20 years.

#### 4.2.2. CSC energy demand

In the CSC no heat option all demand profiles from the BAU case remain unchanged. In the CSC with heat option, however, the building owner can invest into the two passive retrofitting packages shown in Table A.9. These reduce the U-values of the building envelope and thus affect space heating and space cooling demand, ergo also electricity demand. For all passive retrofitting measures a lifetime of 50 years (cf. Wu et al., 2017) is considered.

## 5. Results

In this study we ask two research questions: firstly, under what set of conditions the formation of CSC initiatives employing low-carbon technologies can provide conjoint economic benefits for landlords and renters in MFBs and, secondly, how different CSC regulatory frameworks impact the choice of low-carbon technology options in MFBs and the distribution of economic benefits.

The first question is addressed in Section 5.1. It shows the profitability of forming CSC initiatives in MFBs for all scenarios<sup>4</sup> described in Section 4. The focus is placed on the landlord as the renters always achieve guaranteed savings due to the CSC frameworks and energy-cost-based retrofitting fee. To address our second research question, three case studies are picked out from the 81 MFB configurations

for which the detailed effects of different CSC regulations on economic benefits and low-carbon technology investment are presented in Section 5.2.

### 5.1. Economic feasibility of CSC in MFBs

Fig. 2 shows the results for the profitability analysis of CSC in European MFBs. Almost all scenarios result in a positive owner NPV. For CSC no heat, all scenarios are found to be profitable, while for CSC with heat, unprofitable cases can be found in the two colder climate zones, North Atlantic and Continental, for buildings with medium and high envelope efficiency with low gas prices, 0.08 €/kWh. This threshold remains robust under a 30% increase in investment, while a 30% decrease leads to all scenarios achieving positive NPV. With regards to discount rate increases, the threshold is consistent until a rate of 6% (cf. Fig. C.4), after which scenarios in the colder climates with large retrofitting investments for heating start to show a negative NPV.

Focusing on the differences between climates, the North Atlantic and Continental climate show fairly similar patterns in terms of NPV owner, while the Mediterranean climate exhibits very different trends. The former two are characterized by a smaller spread between CSC regulations due to lower PV production, but show larger differences in NPV (ranging from −€56k to €60k) between the no heat and with heat cases compared to the Mediterranean climate. The larger spread can be explained by the need for larger retrofitting investments in the colder climates (cf. Fig. C.17), whose profitability is also more sensitive to gas costs and efficiency, as seen in Fig. 2, due to the larger heat demand than in the Mediterranean climate.

With respect to energy cost effects, the results show that for a given cost of electricity a higher cost of gas will always lead to a higher NPV with up to a €91k change observed for doubling the gas costs. This is because higher gas costs make the net savings of a HP larger compared to BAU, allowing the owner to raise the rent by a larger amount. For electricity costs, however, the findings indicate that their impact on NPV is case-specific. In all scenarios, an increase in electricity costs has a positive effect on PV revenues. At the same time, it has a negative effect on the savings potential of the HP for the renters and therefore also on the permissible rent increase (cf. Eq. (5)). In scenarios, where the rent increase is already heavily constrained by the low BAU heating costs, i.e. under low gas costs, the latter effect can be predominant and force the owner to invest in more ambitious but costlier energy-efficiency measures leading to a maximum NPV decrease of −€50k for a doubling of electricity costs.

In terms of building efficiency, the results show NPV spreads of up to €63k between MFBs. In almost all scenarios, higher NPVs are recorded for buildings with lower U-values due to the higher permissible rent increase. Some exceptions are found in high efficiency buildings with low gas costs where the lower permissible rent increase is outweighed by the lower required investments for heating retrofits.

To summarize, the results show that:

- CSC initiatives are a win-win situation for MFB owners and renters across large parts of Europe: for CSC no heat across all of Europe and for CSC with heat across all of Europe except in Central and Western European countries with an average U-value of 1.4 W/m<sup>2</sup> K or lower and gas costs of 0.08 €/kWh or less;
- There is little added benefit for MFB owners to invest in CSC with heat compared to CSC no heat: for Southern European countries in general, for Central and Western European countries with gas costs of 0.08 €/kWh or less, and for Central and Western European countries with gas costs 0.12 €/kWh or less and MFBs with average U-values of 1.4 W/m<sup>2</sup> K or lower;
- CSC profitability determinants are highly case-specific: CSC regulation has a larger impact in climates with higher solar irradiance, while envelope efficiency has a larger impact in climates

<sup>4</sup> The variation in envelope efficiency is not shown for the CSC no heat configuration as the results are almost indistinguishable, i.e. the variation of cooling electricity between envelope efficiency levels does not have a strong impact on the results.

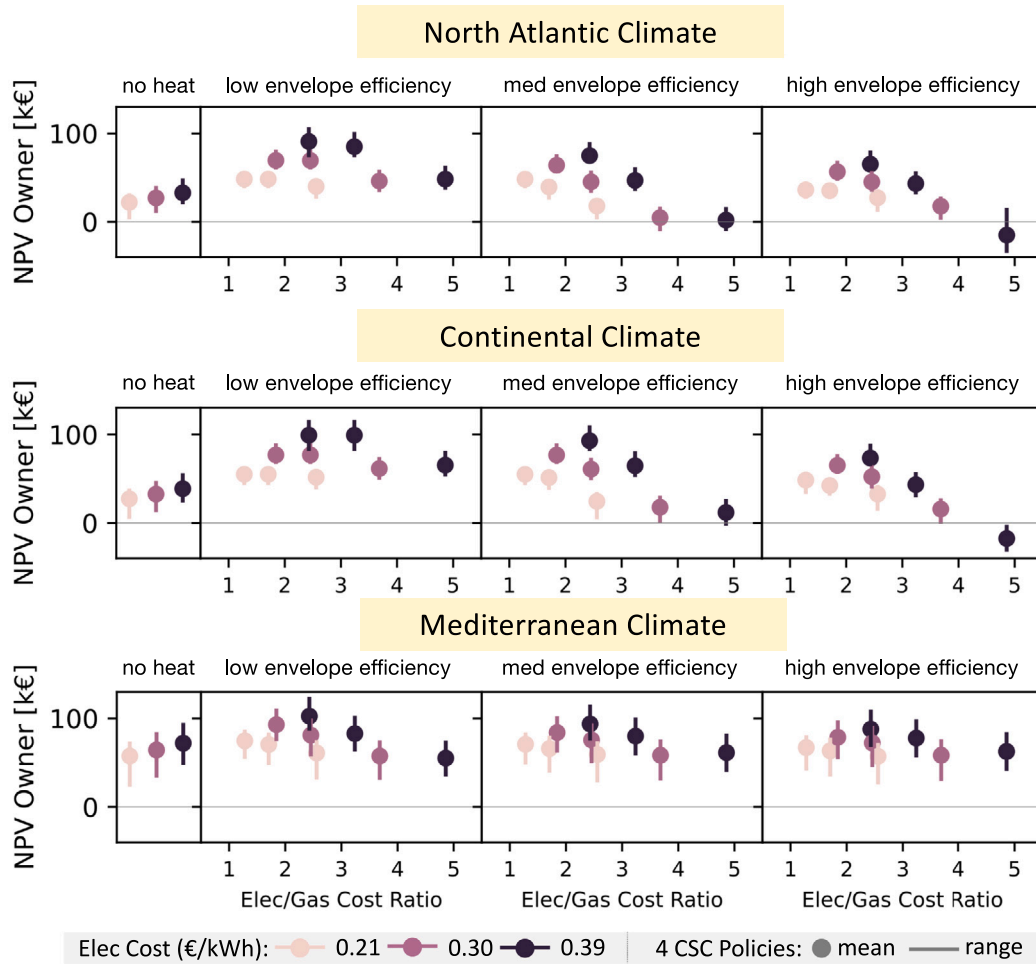


Fig. 2. Displays the NPV to the building owner for CSC with and without heat in a MFB with three different envelope efficiency levels in different climate zones under varying energy costs and CSC regulatory frameworks. Different electricity cost levels are reflected by the colors of the dots. Varying gas cost levels are represented on the x-axis using the electricity to gas cost ratio, where a higher ratio for a given electricity cost, i.e. color, is achieved with a lower gas cost. The effect of CSC regulation is highlighted by the colored range bars showing the spread between the most profitable and least profitable framework and by the colored dot indicating the average between the four frameworks. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with lower temperatures. Also, the impact of gas costs is larger for lower gas costs and is always positive, while the impact of electricity costs increases for high gas costs and changes sign.

## 5.2. Impact of regulatory frameworks on CSC benefits and low-carbon technology investment

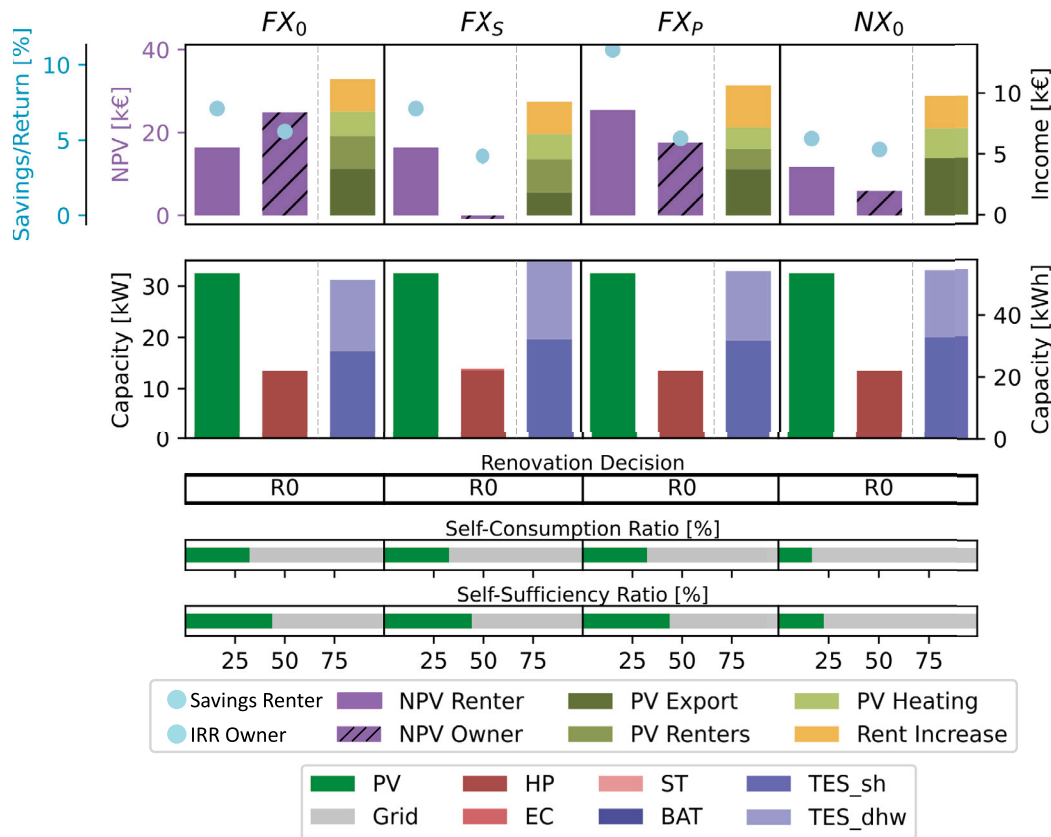
Fig. 3 shows the impact of the four CSC regulatory frameworks on the distribution of benefits between owners and renters, low-carbon technology investment and PV system operation for the Munich case study. The results for London and Lisbon case studies are provided in Appendix C, which also features a statistical analysis of the results for the other model runs.

For Munich it can be seen that the distribution of CSC benefits between owners and renters greatly varies between frameworks, while investment into low-carbon technologies is almost identical. Namely, the renovation of the MFB to the usual level (R1), the installation of a 14 kW HP, a 50–57 kWh TES system, and 33 kW of PV panels corresponding to the maximum roof area of 217 m<sup>2</sup>. In terms of CSC benefits, the owner fairs best under the  $FX_0$  regulation achieving an NPV of €25k and an internal rate of return of 5.6%, followed by the  $FX_P$ ,  $NX_0$ , and  $FX_S$  frameworks, where owner benefits range from €18k to –€1k in terms of NPV or from 5.1 to 3.9% in terms of return rate. For the renters, the highest NPV is reached under the low CSC electricity prices in the  $FX_P$  regulation, amounting to €25k or 11%

savings on the energy bill with  $FX_S$ ,  $FX_0$ , and  $NX_0$  following at 7%, 7%, and 5%.

Overall, the differences in economic results between CSC regulations for both parties can be traced back to variations in annual cash flows and PV system operation. In the  $FX_0$  variant, i.e. where surplus is remunerated at market price and full grid tariff and tax exemptions for CSC electricity apply, annual PV revenues are the largest at €8.5k and a total self-consumption (SCR) and self-sufficiency ratio (SSR) of 32% and 44% are achieved. Lowering surplus remuneration ( $FX_S$ ) mainly leads to a sharp decline of PV Export revenues by 50% and an almost unchanged SCR and SSR. Decreasing the price of CSC electricity ( $FX_P$ ) also does not affect the SCR and SSR but reduces the total PV revenues by 15% and leads to reduced electricity flows to PV Renters and increased ones to PV Heating. Removing grid tariff and tax exemptions for CSC electricity ( $NX_0$ ) results in a 23% increase in PV Heating and Exports but fails to stimulate CSC as the owner does not sell any PV electricity directly to renters resulting in the lowest SCR and SSR of 17% and 23%. Regarding additional rent income, only decreasing the price of CSC electricity ( $FX_P$ ) has a noticeable effect, i.e. an increase of 28%, compared to  $FX_0$  variant.

In the results for Lisbon and London the same impact of different CSC regulation on PV cash flows are found as described above. In terms of low-carbon technology investment, CSC regulatory frameworks mainly influence the sizing of TES and EH in both cities. A noticeable exception is the  $FX_S$  framework in London, where a 19



**Fig. 3.** Munich case study: continental climate, medium envelope  $\eta$ , 0.08 €/kWh gas cost, 0.39 €/kWh electricity cost, and four CSC regulations (cf. Table 6). In the utmost row of the plot, the *NPV* and savings/return rate for both renters and owners is shown for the CSC with heat option on the left y-axis. In addition, all positive annual owner cash flow components, i.e. PV Export (exporting PV electricity to the grid), PV Renters (renters consuming PV electricity), PV Heating (heating system consuming PV electricity), and Rent Increase, are shown on the right y-axis. In the second row, the installed capacities are displayed on the left y-axis for conversion technologies and on the right y-axis for storage technologies. In the third row the chosen passive retrofitting package is displayed. The final two rows show the self-consumption and self-sufficiency ratios.

kWh battery<sup>5</sup> is installed, resulting in a SCR and SSR of 47% and 62% and 59% increase in PV Renters revenues. The statistical results for all scenarios in Appendix C, however, show that, apart from TES, the different regulations have a limited impact on the median capacities of different low-carbon technologies.

In brief, it can be seen that:

- 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.

## 6. Discussion

In Section 6.1 the main findings are discussed and compared with existing results or policy goals. Section 6.2 provides a critical discussion of the chosen method and assumptions.

### 6.1. Discussion of the results

Our analysis demonstrates the positive economic benefits that both landlord and tenants can obtain by forming low-carbon CSC initiatives across a large range of conditions. Although the analyzed scenarios

reflect renter-occupied gas-heated MFBs in Europe, the results are likely to be relevant for a large range of contexts. Examples include countries with similar CSC regulations and climates, e.g. Australia and USA (Jäger-Waldau et al., 2020), MFBs with other non-electric heating systems, and also MFBs with owner-occupiers, whose benefits are equal to the sum of owner and renter benefits.

By installing a PV system for CSC, the owner gains additional revenues through the sale of PV electricity — to the renters directly or also to a centralized HP. At the same time, the renters benefit from lower energy costs achieving average savings of 2.4–6.9% for CSC no heat and 7.4–13.3% for CSC with heat (depending on the CSC framework) relative to their original energy bill. In forming CSC initiatives with low-carbon technologies, both parties achieve a positive NPV in 421 out of 432 scenarios. This share will increase when considering lower heat savings targets (cf. Eq. (5)) for renters that already face low BAU heating costs, i.e. in medium-high efficiency MFB with low gas costs. The widespread positive outcome of CSC for owners and renters highlights its potential to contribute to the EU-policy goals (European Parliament and Council of the European Union, 2018) of jointly tackling climate change and energy poverty by improving energy-efficiency and low-carbon technology adoption in buildings.

For the CSC scenarios without heat, the profitability across all boundary conditions agrees with the findings from previous national case studies (Canova et al., 2022; Braeuer et al., 2022; Villalonga Palou et al., 2023) but also suggests that the low PV deployment on MFBs currently witnessed in many jurisdictions (Fina et al., 2021) could be caused by a lack of capital and/or non-economic barriers, such as informational asymmetries (Hammerle et al., 2023), administrative burdens (Villalonga Palou et al., 2023), technical and regulatory

<sup>5</sup> Out of all 360 scenarios in Fig. 2 a battery is installed in 19 cases, all of which assume the highest electricity cost level and the  $FX_S$  policy.

complexity of CSC operations (Vernay et al., 2023) or limited grid access (Wainer et al., 2022).

For the CSC scenarios with heat, the higher profitability for MFBs with low envelope efficiency supports the findings from Braeuer et al. (2022), now also accounting for renovation costs. Since poorly-insulated buildings are often synonymous with energy poverty (Atanasiu et al., 2014; European Commission, 2020), the results further demonstrate the potential of CSC to help alleviate energy poverty and make energy services more affordable and accessible to the most vulnerable households. On the flip side for MFBs with higher-efficiency envelopes, the results reveal that the formation of CSC projects with HP could be particularly hard in Central and Western European countries with low gas prices, as HP are not cost-competitive with GB in these circumstances as shown by Zwickl-Bernhard et al. (2022) and Barnes and Bhagavathy (2020).

Looking at the difference in profitability between no heat and with heat scenarios reveals additional split incentives for decarbonizing heating in renter-occupied MFBs in all three considered climate zones. That is because the gain for building owners to install PV and a HP compared to a PV only system is either negligible in the Mediterranean climate or even negative in medium-high envelope efficiency MFBs with low gas costs in the North Atlantic and Continental climate while requiring much larger upfront investments. These findings suggest that the transition to low-carbon heat in MFBs will require additional support measures for building owners.

With respect to designing these support measures, the results show that the most impactful profitability levers for building owners in CSC with heat projects differ across climate zones. For the affected cases in the northern climates, gas costs are a stronger profitability determinant than electricity costs with CSC regulation only having a marginal impact except for the 4.85 electricity gas ratio case in the high-efficiency MFB in the North Atlantic climate. In the Mediterranean climate, on the other hand, the impacts of energy costs and CSC regulation appear to be more on a similar level, which opens up the opportunity to use more beneficial CSC regulatory frameworks to incentivize CSC with heat projects.

Apart from having a climate-dependent impact on building owner benefits, the results also suggest that CSC regulations have a large effect on the operation of the PV system and only a limited one on low-carbon technology investment. Moreover, the findings indicate that specific CSC regulatory features favor some stakeholders over others. Grid tariff and tax exemptions for CSC electricity lead to reduced feed-in and higher local consumption, which is particularly important for the renters as their savings depend on the self-sufficiency level. However, such exemptions have been shown to have a negative system wide impact by raising overall regulated tariff components for consumers tied to a centralized supply (Gunkel et al., 2023). In addition, the results for different CSC regulations suggest that the level of surplus remuneration has a large effect on self-consumption ratios and overall PV revenues for the owner but contrary to previous findings (Gallego-Castillo et al., 2021; Gil Mena et al., 2023) does not affect the installed capacity of the PV system. This difference arises from the fact that the owner would like to install higher PV capacities due to feed-in at historically high market prices in this study but is constrained by the maximum roof area. Moreover, the results demonstrate that different pricing levels for shared electricity simply reallocate the benefits of the PV system between the owners and renters in CSC no heat configurations as determined by Fleischhacker et al. (2019). For the CSC with heat scenarios, however, the results show that lower CSC pricing is very beneficial for the renters but has not such a large economic impact on the owner. The reason for the latter is that lower CSC prices also make PV heating cheaper thus permitting the owner to raise the rent by a larger amount, which partially compensates for the reduced PV revenues.

## 6.2. Limitations

Several assumptions and methodological choices made in this study have to be viewed critically.

With respect to the representation of electricity costs several limitations have to be considered. The first relates to the fact that electricity prices are exogenously given in this study. This means that there is no system feedback and the results, therefore, represent the benefits for first movers. The more widespread appearance of flexible consumers, such as CSC initiatives, will likely lead to a shift in electricity supply and demand patterns thus impacting market prices. The second regards the 100% volumetric cost structure for grid tariffs and electricity taxes. For countries with larger fixed tariff components, e.g. based on contracted power, the achievable benefits for owners and renters will lie between the values obtained for the *NX* and *FX* regulatory variants in this study.

Regarding owner benefits, the consideration of income taxes, administrative, and transaction costs will lead to a reduction thereof. Similarly, annual PV revenues could decrease if some renters decided to opt-out of the CSC scheme. Conversely, passive retrofitting investment is likely to be lower for the building owner if more granular retrofitting measures (instead of packages), the option to retrofit low-temperature radiators and the possibility to wait until general renovation is due are considered.

In terms of renter benefits, the savings could differ for a number of reasons in a specific CSC project. First of all, they are aggregated at a building level. In practice, depending on the PV allocation mechanism and their individual consumption behavior, some tenants will gain more from joining the CSC scheme than others (Roberts et al., 2022). Secondly, the use of fixed load profiles does not allow the renters to shift their electricity demand to periods of high irradiance thus underestimating CSC benefits. In addition, the use of a fixed temperature comfort limit across all building types is likely to inflate the savings potential for passive retrofitting, as residents of poorly insulated buildings are known to accept lower comfort levels (Vadodaria et al., 2014). Furthermore, the savings from switching to a HP are uncertain. This is because it is unknown if the grid imports to the collective HP will be billed at a price for large household consumers or small business consumers. In Switzerland, for example the difference amounts to 0.04 €/kWh (Eidgenössische Elektrizitätskommission ElCom, 2023) for a consumption of 25.000 kWh per year. Similarly, the operation of the thermal storage for the HP is likely to be costlier in a real-world implementation due to the use of predictive controllers with imperfect foresight.

Finally also limitations with respect to the space heating and cooling load modeling have to be taken in to account. While some authors deem the RC model employed in this study suitable for thermal load modeling based on validation with standardized test cases (Schütz et al., 2017) and detailed simulation models (Michalak, 2014), others have questioned its suitability for predicting MFB heating loads (Bruno et al., 2016) and recommend the use of RC models with more capacities (Sperber et al., 2020). In addition, the thermal loads are only considered for a single year and do not account for future changes in cooling and heating demand caused by climate change.

## 7. Conclusion and policy implications

CSC initiatives are seen as a promising way to accelerate decarbonization efforts in MFBs while creating benefits for all participants. In this study, therefore, the questions are posed under what set of conditions the formation of CSC initiatives employing low-carbon technologies can provide conjoint economic benefits for landlords and renters in MFBs and, secondly, how different CSC regulatory frameworks impact the choice of low-carbon technology options in MFBs and the distribution of economic benefits.



To address these questions, four CSC regulation scenarios are integrated into a newly-developed mixed-integer linear optimization model, which determines the optimal selection and operation of low-carbon technologies for a renter-occupied MFB considering various technology options, energy costs, and building envelope efficiency levels, and climate zones. The employed model maximizes the benefits of the building owner while guaranteeing a minimum level of savings for the renters. The main novelty of this approach lies in the broad scope across Europe and the context-specific analysis of CSC profitability determinants.

The results show that CSC in MFBs can provide conjoint benefits for building owners and renters across Europe, except in buildings with medium–high envelope efficiency under low gas prices in Western and Central European climates. However in all European climate zones, remaining split incentives in renter-occupied MFBs for decarbonizing heating are found. While the results show generally similar choices of low-carbon technologies under the different CSC frameworks, large differences in the magnitude and distribution of benefits of the PV system are observed.

Overall, the findings highlight the potential for CSC initiatives to contribute to an equitable and sustainable energy transition and hold three main implications for policy makers.

First of all, policy makers should consider implementing supportive frameworks for CSC. Our analysis suggests economic viability is not the main issue. Therefore, such frameworks should focus on overcoming non-economic barriers, such as increasing awareness to building owners and tenants, guaranteeing access to low-cost financing, reducing regulatory complexity and providing technical assistance to CSC projects.

Secondly, there is a need to overcome remaining split incentives for decarbonizing heating in renter-occupied MFBs. In Southern European climates, this could be achieved by offering higher tax exemptions for shared electricity in CSC projects with HP or by offering them more attractive surplus remuneration schemes, while the generally lower impact of CSC regulation in the Central and Western climates necessitates additional support measures. These could be given in the form of HP and renovation subsidies or reduced electricity taxes for HP electricity, while raising taxes on gas is not recommended despite being the most impactful option as this would engender higher energy bills for tenants in the short term.

Finally, as the results show robust positive returns for building owners under many different CSC regulation scenarios and boundary conditions, future CSC policy design could focus on increasing renter benefits and positive system wide impacts without a significant profitability penalty for owners, especially in climates with lower solar irradiance.

This study has shed light on aggregated economic benefits for owners and renters forming an CSC initiative in a MFB under different CSC regulatory frameworks. However, open questions remain about the impact of CSC operations on the distribution grid and on individual tenant households with distinct socio-economic characteristics. Future work should, therefore, perform detailed social cost–benefit-analyses of CSC regulations including impacts on individual tenants and the low-voltage network so that the interests of different stakeholders can be adequately accounted for and a fair distribution of decarbonization benefits can be ensured. Subsequent approaches should also consider the load-shifting potential of CSC projects and endogenous electricity prices to explore the impact of a widespread adoption of distributed energy technologies and smart home energy management systems.

#### CRedit authorship contribution statement

**Christoph Domenig:** Conceptualization, Methodology, Software, Visualisation, Formal analysis, Writing – original draft, Writing – review & editing. **Fabian Scheller:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Phillipp Andreas Gunkel:**

Conceptualization, Methodology, Writing – review & editing, Supervision. **Julian Hermann:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Claire-Marie Bergaentzlé:** Conceptualization, Writing – review & editing, Supervision. **Marta A.R. Lopes:** Conceptualization, Writing – review & editing. **Jake Barnes:** Conceptualization, Writing – review & editing. **Russell McKenna:** Methodology, Writing – review & editing, Supervision, Project administration.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Disclaimers

The views and opinions expressed in this paper are those of the authors and do not necessarily reflect the official policy or position of Nordic RCC.

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#### Appendix A. Techno-economic parameters

The operation costs for the heating system have to be paid by the renters. These are calculated as introduced Section 3.3, i.e. based on a fixed percentage of the heating system investment. For the BAU case, the capacity  $Cap_{bau}$  is sized on the peak heating load  $\max_t(\dot{Q}_{bau,t}^{sh} + \dot{Q}_{bau,t}^{dhw})$  of the unrenovated building (R0) taking the conversion efficiency  $\eta_{bau}^{sh}$  into account. For the gas boiler a specific investment of  $c_{bau}^{var}$  100 €/kW, a fixed investment of  $c_{bau}^{fix}$  €2800, and an operation cost of  $c_{bau}^{opex}$  1.5% is assumed; all techno-economic parameters for the gas boiler are taken from Kotzur (2018).

#### Appendix B. Additional equations for optimization model

##### B.1. Implementation of the CSC policy frameworks

Across all four CSC policy archetypes, non-zero entries for  $M_{i,j,t}^{own}$  or  $M_{i,j,t}^{rent}$  (cf. Tables B.10 and B.11) can be found for five types of energy flows:

- PV Renters: Collectively self-consuming PV electricity by the renters
- PV Heating: Self-consuming PV electricity in the heating system
- PV Export: Exporting PV electricity to the grid
- Grid Renters: Importing grid electricity to the renters
- Grid Heating: Importing grid electricity to the heating system

The main differences between the four policy scenarios, are reflected in PV Renters and PV Export.

In policies  $FX_0$ ,  $FX_S$ , and  $NX_0$  the building owner can sell PV electricity to the renters at 90%<sup>6</sup> of their current cost of electricity  $c_{bau,t}^{el}$ . This cost is composed of the hourly wholesale electricity price  $p_t^{el}$  and additional charges, which consist of grid tariffs, electricity taxes excl. VAT  $\tau_{bau,t}^{gtx}$  and VAT  $\tau^{vat}$ . The resulting total value for  $c_{bau,t}^{el}$  is computed as shown in Eq. (B.1).

$$c_{bau,t}^{el} = (p_t^{el} + \tau_{bau,t}^{gtx}) \cdot (1 + \tau^{vat}) \quad (B.1)$$

<sup>6</sup> This value is based on the German CSC framework (Crowley-Nicol, 2020).



**Table A.7**

Techno-economic parameters for active retrofitting measures.

Name	$c^{fix}$	$c^{var}$	$c^{opex}$	$\eta$	$\lambda$	$\delta$	$Cap^{max}$	$L$	Source
PV	1000 €	203 <sup>b</sup> €/m <sup>2</sup>	1%	0.15	–	–	217 m <sup>2</sup>	20 y	Brauer et al. (2022), $\eta$ : Wu et al. (2017), $c^{opex}$ : Kotzur (2018)
ST	4000 €	350 €/m <sup>2</sup>	1%	0.7	–	–	217 m <sup>2</sup>	20 y	Kotzur (2018), $\eta$ : Wu et al. (2017)
EH	0 €	60 €/kW	2%	1	–	–	5 kW	30 y	Kotzur (2018), $\eta$ : Wu et al. (2017)
HP	5000 €	600 €/kW	2%	$a_0 = 5.06$ , $a_1 = -0.05$ , $a_2 = 0.00006$	–	–	30 kW	20 y	Kotzur (2018), $\eta$ : Fischer et al. (2017)
TES	800 €	35 <sup>c</sup> €/kWh	0%	0.99	0.6%	1.0	200 kWh	25 y	Kotzur (2018)
BAT	2000 €	530 €/kWh	2%	0.95	0.01%	0.5	200 kWh	15 y	Kotzur (2018), $c^{fix/var}$ : Brauer et al. (2022)

<sup>a</sup>  $Cap_{el}^{max}$  is assumed to be 230 kW for the entire building.<sup>b</sup> Converted from €/kWp to €/m<sup>2</sup> using  $\eta$ .<sup>c</sup> Converted from €/l to €/kWh based on a temperature difference of 30 °C.**Table A.8**Building U-values (W/m<sup>2</sup> K) and heating curve coefficients. R0 U-values and renovation measures taken from Loga et al. (2016). Heating curves obtained from Viessmann (2016).

Envelope efficiency	$r$	$U_{roof}$	$U_{wall}$	$U_{floor}$	$U_{window}$	$b_0$	$b_1$	$b_2$
Low	R0	3.5	2.2	0.85	5	64.17	-2.13	-0.0042
	R1	0.27	0.26	0.29	1.3	39.78	-0.88	-0.0056
	R2	0.11	0.14	0.22	0.8	38.08	-0.79	-0.0058
Medium	R0	1.081	1.2	1.33	3.0	53.13	-1.47	-0.0092
	R1	0.23	0.23	0.33	1.3	39.68	-0.87	-0.0056
	R2	0.105	0.13	0.24	0.8	38.09	-0.79	-0.0058
High	R0	0.357	0.6	0.51	3.0	44.43	-1.10	-0.0063
	R1	0.161	0.2	0.24	1.3	39.05	-0.84	-0.0057
	R2	0.088	0.12	0.19	0.8	37.83	-0.78	-0.0058

In  $FX_0$  and  $FX_S$ , the building owner then receives the net amount of  $c_{bau,t}^{el}$  for PV Renters, i.e. without  $\tau^{vat}$ . In  $NX_0$ , however, the renters are not exempt from paying  $\tau^{gtx}$  on this energy flow. These are costs that need to be factored into the owner's price for PV Renters so that the renters can still save 10% on PV Renters versus  $c_{bau,t}^{el}$  as assumed above. In policy  $FX_P$ , PV Renters is priced halfway between the cost the renters have to pay for importing electricity  $c_{bau,t}^{el}$  and the amount the owner gets for selling PV Exports, here assumed to be the wholesale price  $p_t^{el}$ .

For PV Export, the assumption is made in  $FX_0$ ,  $FX_P$ , and  $NX_0$  that the owner exports PV surplus at the hourly wholesale electricity price  $p_t^{el}$ . In  $FX_S$ , the surplus is remunerated at half of the market value.

In all four policy scenarios, it is assumed that PV Heating is priced the same as PV Renters and is counted as self-consumption thus fully exempt of grid tariffs and taxes. For the remaining heating imports, Grid Heating, the owner purchases heating electricity at a reduced cost for large consumers  $c_{HP/EH,t}^{el}$  and passes on this cost to renters. In contrast, for Grid Renters, it is assumed that the owner is not involved as intermediary buyer and the renters directly pay  $c_t^{bau}$  to their electricity provider.

$$c_{HP/EH,t}^{el} = (p_t^{el} + \tau_{HP/EH}^{gtx}) \cdot (1 + \tau^{vat}) \quad (B.2)$$

## B.2. Technical constraints

The design, sizing, and operation of the building energy technologies has to guarantee the supply of the MFB's electrical and thermal demands while complying with multiple technical constraints. These include energy balances for the conversion technology, storage system,

and demand nodes and general technical constraints imposed by the building and its energy systems.

General technical constraints will be presented first. These include all energy flows being non-negative for all time steps  $t$  (Eq. (B.3)) and energy flows  $P_{i,j,t}$  between nodes  $i$  and  $j$  being set to zero if the energy carrier of their outputs  $out$  and input  $in$  do not match (Eq. (B.4)). For example,  $P_{HP,BAT,t}$  is set to zero because the HP outputs, sh and dhw, do not match the electricity (el) input of the battery.

$$0 \leq P_{i,j,t} \quad \forall i, j, t \quad (B.3)$$

$$P_{i,j,t} = 0 \quad \forall t, \{i, j \mid i_{out} \cap j_{in} = 0\} \quad (B.4)$$

Additional energy flows that are set to zero include electricity exports (elxp) from storage systems, instantaneous grid electricity exports (Eq. (B.5)), and electricity imports to storages (Eq. (B.6)). These two equations combined ensure that storage systems cannot be used for arbitrage operations. Furthermore, no flows between storages are allowed in Eq. (B.7).

$$P_{i,elxp,t} = 0 \quad \forall t, i \in \{el, k\} \quad (B.5)$$

$$P_{el,k,t} = 0 \quad \forall t, k \quad (B.6)$$

$$P_{i,k,t} = 0 \quad \forall t, k, i \in \{k\} \quad (B.7)$$

DHW tanks have to be installed (Eq. (B.8)), and DHW demand can only be served from the  $TES_{dhw}$  and not by the conversion technologies directly (Eq. (B.9)).

$$X_{TES_{dhw}} = 1 \quad (B.8)$$

$$P_{g,dhw,t} = 0 \quad \forall g, t \quad (B.9)$$

Eq. (B.10) ensures that one of the three passive retrofitting options is chosen.

$$\sum_r X_r = 1 \quad (B.10)$$

Eq. (B.11) ensures that all conversion and storage technology capacities are constrained by  $Cap_x^{max}$  (given in the same units as  $Cap_x$ ) if the active retrofitting measure is chosen and set to zero otherwise.

$$0 \leq Cap_x \leq X_x \cdot Cap_x^{max} \quad \forall x = g \cup k \quad (B.11)$$

The sum of the panel area of all solar-technologies is constrained by the building's roof area  $A_{roof}$  (m<sup>2</sup>) as displayed in Eq. (B.12).

$$\sum_g Cap_g \leq A_{roof} \quad \forall g \in \{PV, ST\} \quad (B.12)$$

**Table A.9**

Passive retrofitting measures.

Source: Cost data taken from [Hinz \(2015\)](#).

$r$	Component	Measure	Cost/Area	Area	Cost €	$c_r^{fix}$ €
R1	Roof	12 cm WLS 035	49.39 €/m <sup>2</sup>	217 m <sup>2</sup>	10,703	90,600 (full)
	Walls (full)	12 cm WLS 035	130.6 €/m <sup>2</sup>	336 m <sup>2</sup>	43,882	
	Walls (EE)	12 cm WLS 035	53.5 €/m <sup>2</sup>	336 m <sup>2</sup>	17,973	
	Floor	8 cm WLS 035	40.75 €/m <sup>2</sup>	217 m <sup>2</sup>	8802	64,680 (EE)
	Windows	Double glazing	334.6 <sup>a</sup> €/m <sup>2</sup>	81 m <sup>2</sup>	27,201	
R2	Roof	30 cm WLS 035	81.43 €/m <sup>2</sup>	217 m <sup>2</sup>	17,646	114,072 (full)
	Walls (full)	24 cm WLS 035	164.3 €/m <sup>2</sup>	336 m <sup>2</sup>	55,212	
	Walls (EE)	24 cm WLS 035	87.2 €/m <sup>2</sup>	336 m <sup>2</sup>	29,303	
	Floor	12 cm WLS 035	45.75 €/m <sup>2</sup>	217 m <sup>2</sup>	9882	88,160 (EE)
	Windows	Triple glazing	385.4 <sup>a</sup> €/m <sup>2</sup>	81 m <sup>2</sup>	31,332	

<sup>a</sup> Assuming a window size of 2.5 m<sup>2</sup>.**Table B.10**

Building owner revenue matrix.

Name	Symbols	$FX_0$	$NX_0$	$FX_S$	$FX_P$
PV Renters	$M_{BAT,el,t}^{own}$	$0.9 \cdot \frac{c_{bau,t}^{el}}{1 + \tau^{vat}}$	$0.9 \cdot \frac{c_{bau,t}^{el}}{1 + \tau^{vat}} - \tau_{small}^{fix}$	$0.9 \cdot \frac{c_{bau,t}^{el}}{1 + \tau^{vat}}$	$0.5 \cdot \frac{(c_{bau,t}^{el} + p_t^{el})}{1 + \tau^{vat}}$
	$M_{PV,el,t}^{own}$				
PV Heating	$M_{PV,HP,t}^{own}$				
	$M_{PV,EH,t}^{own}$	$0.9 \cdot \frac{c_{bau,t}^{el}}{1 + \tau^{vat}}$	$0.9 \cdot \frac{c_{bau,t}^{el}}{1 + \tau^{vat}}$	$0.9 \cdot \frac{c_{bau,t}^{el}}{1 + \tau^{vat}}$	$0.5 \cdot \frac{(c_{bau,t}^{el} + p_t^{el})}{1 + \tau^{vat}}$
	$M_{BAT,HP,t}^{own}$				
	$M_{BAT,EH,t}^{own}$				
PV Export	$M_{PV,exp,t}^{own}$	$p_t^{el}$	$p_t^{el}$	$0.5 \cdot p_t^{el}$	$p_t^{el}$

**Table B.11**

Renter cost matrix.

Name	Symbols	$FX_0$	$NX_0$	$FX_S$	$FX_P$
PV Renters	$M_{PV/BAT,el,t}^{rent}$	$0.9 \cdot c_{bau,t}^{el}$	$0.9 \cdot c_{bau,t}^{el}$	$0.9 \cdot c_{bau,t}^{el}$	$0.5 \cdot (c_{bau,t}^{el} + p_t^{el})$
PV Heating	$M_{PV/BAT,HP/EH,t}^{rent}$	$0.9 \cdot c_{bau,t}^{el}$	$0.9 \cdot c_{bau,t}^{el}$	$0.9 \cdot c_{bau,t}^{el}$	$0.5 \cdot (c_{bau,t}^{el} + p_t^{el})$
Grid Renters	$M_{el,t}^{rent}$	$c_{bau,t}^{el}$	$c_{bau,t}^{el}$	$c_{bau,t}^{el}$	$c_{bau,t}^{el}$
Grid Heating	$M_{el,HP/EH,t}^{rent}$	$c_{HP/EH,t}^{el}$	$c_{HP/EH,t}^{el}$	$c_{HP/EH,t}^{el}$	$c_{HP/EH,t}^{el}$

The total output of a non-solar conversion technology is constrained by its installed thermal capacity (kW) multiplied by the hourly time interval  $\Delta\tau$  (h) as detailed in Eq. (B.13), while the total electricity imports and exports are limited by the maximum power of the building's grid connection point  $Cap_{el}^{max}$  (kW) multiplied by  $\Delta\tau$  in Eqs. (B.14) and (B.15)

$$\sum_j \mathbf{P}_{g,j,t} \leq \mathbf{Cap}_g \cdot \Delta\tau \quad \forall t, g \in \{HP, EH\} \quad (\text{B.13})$$

$$\sum_j \mathbf{P}_{el,j,t} \leq Cap_{el}^{max} \cdot \Delta\tau \quad \forall t \quad (\text{B.14})$$

$$\mathbf{P}_{PV,exp,t} \leq Cap_{el}^{max} \cdot \Delta\tau \quad \forall t \quad (\text{B.15})$$

Energy balances are formulated for all nodes in the model, namely conversion technology, storage, and demand nodes. In conversion technology nodes inputs and outputs of conversion technologies are related through efficiencies  $\eta_g$ . These are kept constant except for the HP, where the efficiency  $\eta_{HP,d,r,t}$  depends on the output energy carrier  $d$ , i.e. SH or DHW, the passive retrofit state of the building  $r$ , and the time step  $t$ . The HP efficiency is modeled as a quadratic function of temperature lift, i.e. difference between heat supply  $T_{d,r,t}^{sup}$  and ambient temperature  $T_t^{amb}$ , as shown in Eq. (B.16). DHW is assumed to be supplied at a constant supply temperature  $T_{dhw}$  and SH at a variable

supply temperature based on a  $r$ -dependent quadratic heating curve as described in Eqs. (B.17) and (B.18) respectively.

$$\eta_{HP,d,r,t} = a_0 + a_1 \cdot (T_{d,r,t}^{sup} - T_t^{amb}) + a_2 \cdot (T_{d,r,t}^{sup} - T_t^{amb})^2 \quad (\text{B.16})$$

$$T_{dhw,r,t}^{sup} = T_{dhw} \quad (\text{B.17})$$

$$T_{sh,r,t}^{sup} = b'_0 + b'_1 \cdot (T_t^{amb}) + b'_2 \cdot (T_t^{amb})^2 \quad (\text{B.18})$$

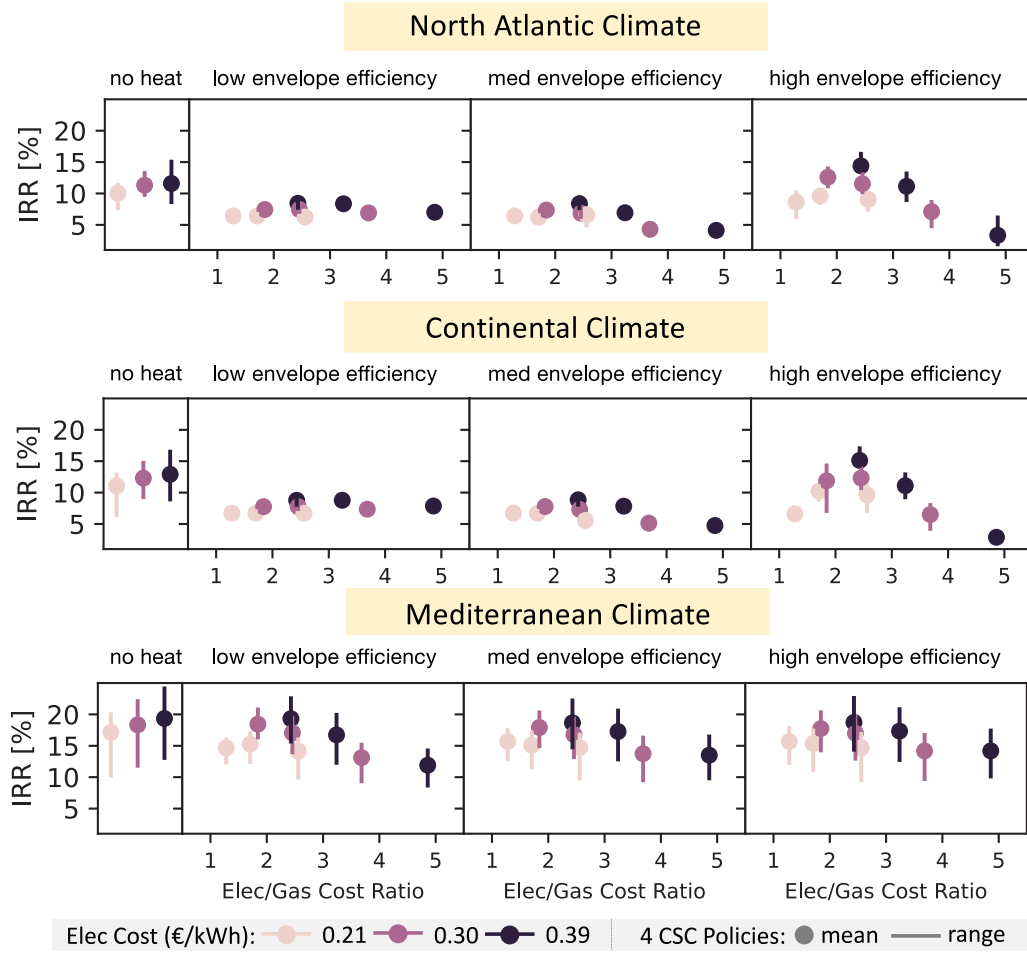
Eqs. (B.19), (B.20), and (B.21) ensure that all inputs to a conversion technology are equal to all of its outputs weighted by its efficiencies. For solar technologies, the input is equal to the global solar irradiance  $I_t$  (kW/m<sup>2</sup>) times the panel area (m<sup>2</sup>) of the solar technology  $\mathbf{Cap}_{PV/ST}$  times  $\Delta\tau$ , while for non-solar technologies inputs are equal to energy flows from other conversion technologies and storage systems as well as energy imports. The products of binary and continuous variables in Eq. (B.21) are linearized using the big M method.

$$I_t \cdot \Delta\tau \cdot \mathbf{Cap}_g = \sum_j \left( \frac{1}{\eta_g} \cdot \mathbf{P}_{g,j,t} \right) \quad \forall t, g \in \{PV, ST\} \quad (\text{B.19})$$

$$\sum_i \mathbf{P}_{i,EH,t} = \sum_j \left( \frac{1}{\eta_{EH}} \cdot \mathbf{P}_{EH,j,t} \right) \quad \forall t \quad (\text{B.20})$$

$$\sum_i \mathbf{P}_{i,HP,t} = \sum_r \sum_j \sum_d \left( X_r \cdot \frac{1}{\eta_{HP,d,r,t}} \cdot \mathbf{P}_{HP,j,t} \right) \quad \forall t \quad (\text{B.21})$$

In storage nodes, the outputs of technologies can be stored in energy storage systems. These are modeled using a state of charge (SOC) variable  $S_{k,t}$  (kWh), which is constrained by the installed capacity of the storage system in Eq. (B.22). Eq. (B.23) relates the SOC of the first time step  $S_{k,1}$  to the initial SOC  $S_k^0$  (kWh), while Eq. (B.24) defines the evolution of  $S_{k,t}$  for all subsequent time steps. The SOC can be changed by charging or discharging the storage with efficiency  $\eta_k^{cd}$  or through



**Fig. C.4.** Displays the internal rate of return for the building owner for CSC with and without heat in a MFB with three different envelope efficiency levels in different climate zones under varying energy costs and CSC regulatory frameworks. Different electricity cost levels are reflected by the colors of the dots. Varying gas cost levels are represented on the x-axis using the electricity to gas cost ratio, where a higher ratio for a given electricity cost, i.e. color, is achieved with a lower gas cost. The effect of CSC regulation is highlighted by the colored range bars showing the spread between the most profitable and least profitable framework and by the colored dot indicating the average between the four frameworks. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

self-discharge losses  $\lambda_k$ .

$$0 \leq S_{k,t} \leq \text{Cap}_k \quad \forall k, t \quad (\text{B.22})$$

$$S_{k,1} = (X_k \cdot S_k^0) \cdot (1 - \lambda_k) + \eta_k^{cd} \cdot \sum_i P_{i,k,t} + \frac{1}{\eta_k^{cd}} \cdot \sum_j P_{k,j,t} \quad \forall k \quad (\text{B.23})$$

$$S_{k,t} = S_{k,t-1} \cdot (1 - \lambda_k) + \eta_k^{cd} \cdot \sum_i P_{i,k,t} + \frac{1}{\eta_k^{cd}} \cdot \sum_j P_{k,j,t} \quad \forall k, \{t \mid 1 < t \leq T\} \quad (\text{B.24})$$

The charging and discharging flows are limited by fraction  $\delta_k$  of the installed storage capacity in Eqs. (B.25) and (B.26). Furthermore, the cyclical constraint in Eq. (B.27) ensures that the storage system is not left completely discharged in the last time step  $T$ .

$$\sum_i P_{i,k,t} \leq \text{Cap}_k \cdot \delta_k \quad \forall k, t \quad (\text{B.25})$$

$$\sum_j P_{k,j,t} \leq \text{Cap}_k \cdot \delta_k \quad \forall k, t \quad (\text{B.26})$$

$$S_{k,T} = X_k \cdot S_k^0 \quad \forall k \quad (\text{B.27})$$

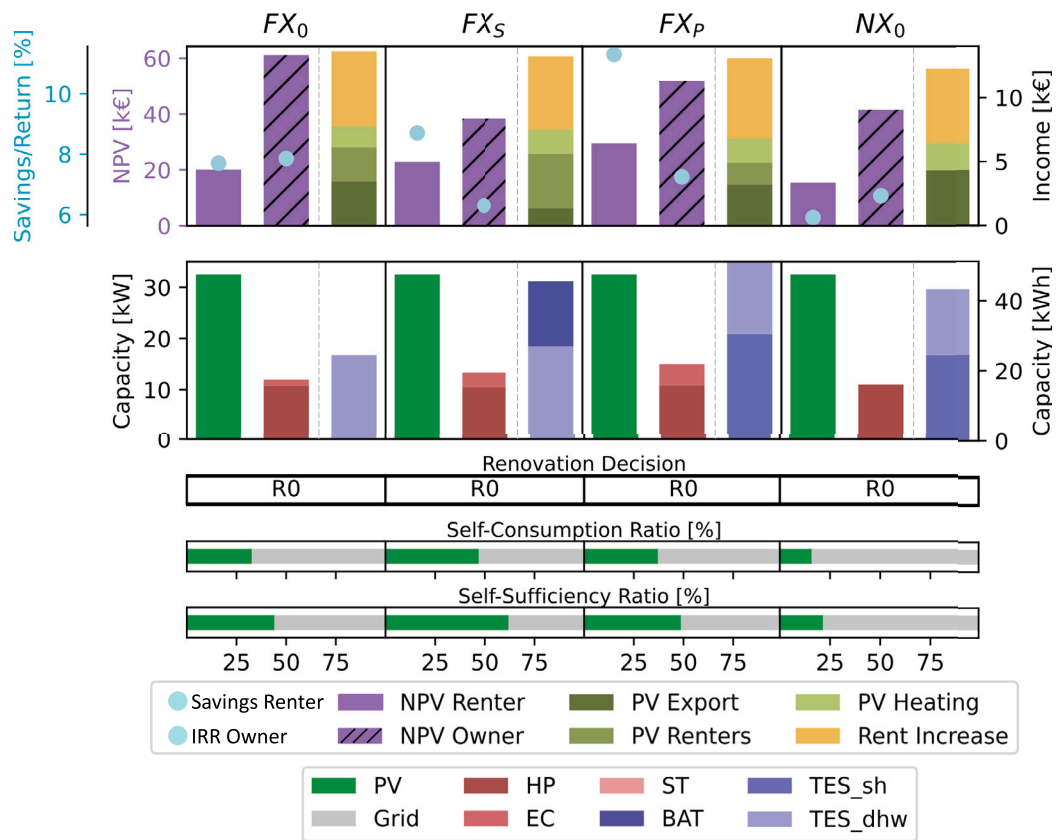
In demand nodes, all energy flows from conversion technologies, storage systems or the electricity grid have to satisfy the thermal and electric loads of the building as shown in Eqs. (B.28) and (B.29). The DHW load  $\dot{Q}_t^{dhw}$  is independent of the renovation level of the building, whereas the SH and electricity demands  $\dot{Q}_{r,t}^{sh}$  and  $\dot{Q}_{r,t}^{el}$  depend on the passive retrofitting measures chosen in the optimization. All demands are extraneously given (in kW).

$$\sum_i P_{i,dhw,t} = \dot{Q}_t^{dhw} \cdot \Delta\tau \quad \forall t \quad (\text{B.28})$$

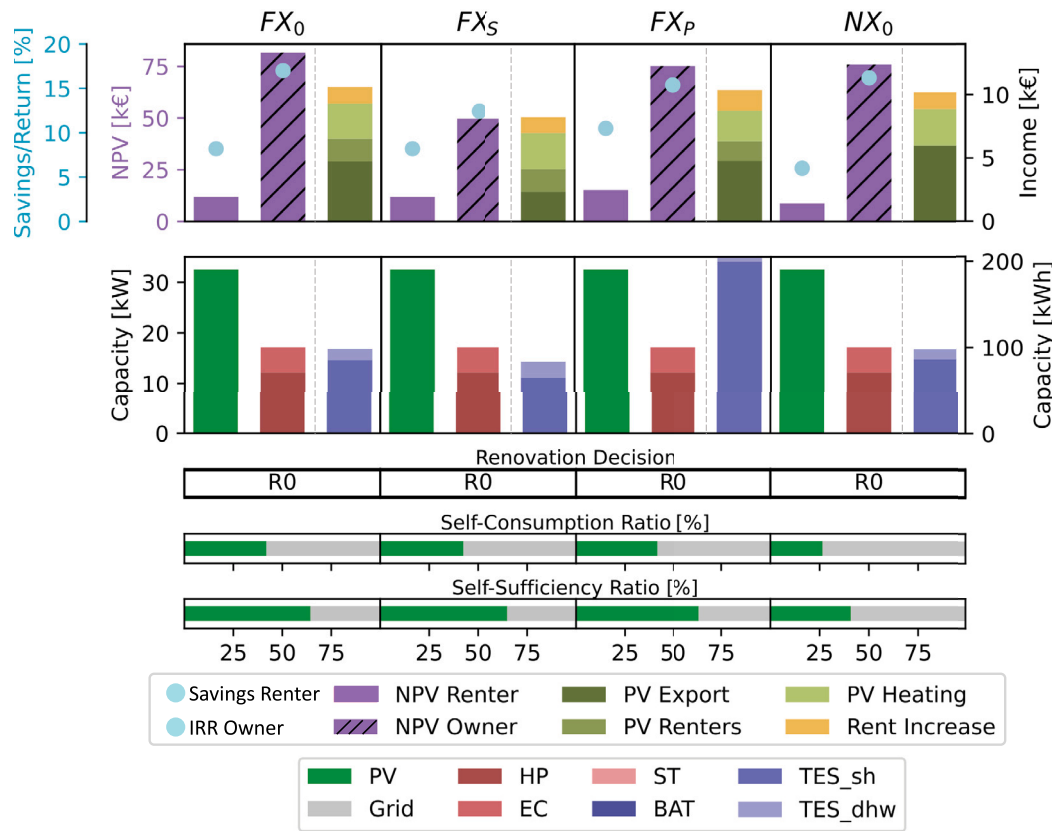
$$\sum_i P_{i,d,t} = \sum_r X_r \cdot \dot{Q}_{r,t}^d \cdot \Delta\tau \quad \forall t, d \in \{el, sh\} \quad (\text{B.29})$$

## Appendix C. Additional results

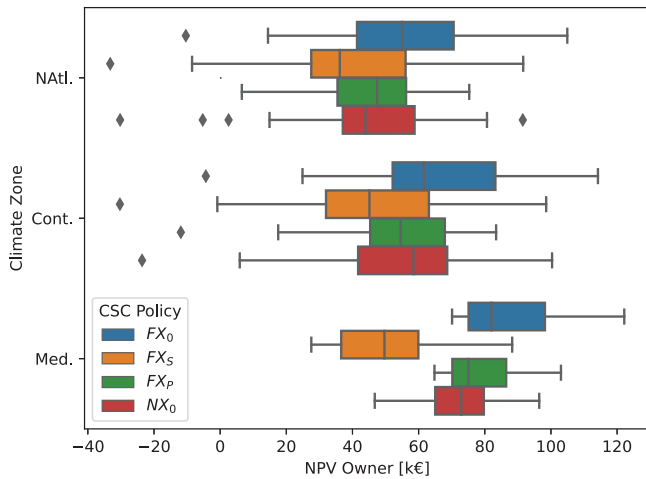
See Figs. C.4–C.16.



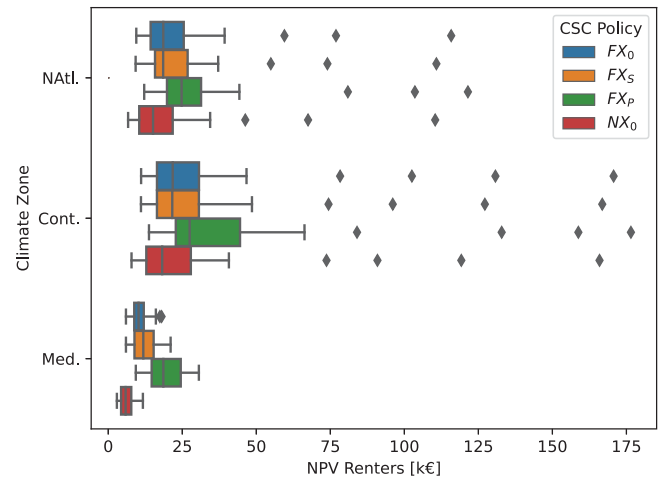
**Fig. C.5.** London case study: low envelope efficiency MFB, 0.08 €/kWh gas, 0.39 €/kWh electricity, and four CSC regulations (cf. Table 6). In the upmost row of the plot, the *NPV* and savings/return rate for both renters and owners is shown for the CSC with heat option on the left y-axis. In addition, all positive annual owner cash flow components, i.e. PV Export (exporting PV electricity to the grid), PV Renters (renters consuming PV electricity), PV Heating (heating system consuming PV electricity), and Rent Increase, are shown on the right y-axis. In the second row, the installed capacities are displayed on the left y-axis for conversion technologies and on the right y-axis for storage technologies. In the third row the chosen passive retrofitting package is displayed. The final two rows show the self-consumption and self-sufficiency ratios.



**Fig. C.6.** Lisbon case study: low envelope efficiency MFB, 0.12 €/kWh gas, 0.21 €/kWh electricity, four CSC regulations (cf. Table 6). In the upmost row of the plot, the  $NPV$  and savings/return rate for both renters and owners is shown for the CSC with heat option on the left y-axis. In addition, all positive annual owner cash flow components, i.e. PV Export (exporting PV electricity to the grid), PV Renters (renters consuming PV electricity), PV Heating (heating system consuming PV electricity), and Rent Increase, are shown on the right y-axis. In the second row, the installed capacities are displayed on the left y-axis for conversion technologies and on the right y-axis for storage technologies. In the third row the chosen passive retrofitting package is displayed. The final two rows show the self-consumption and self-sufficiency ratios.

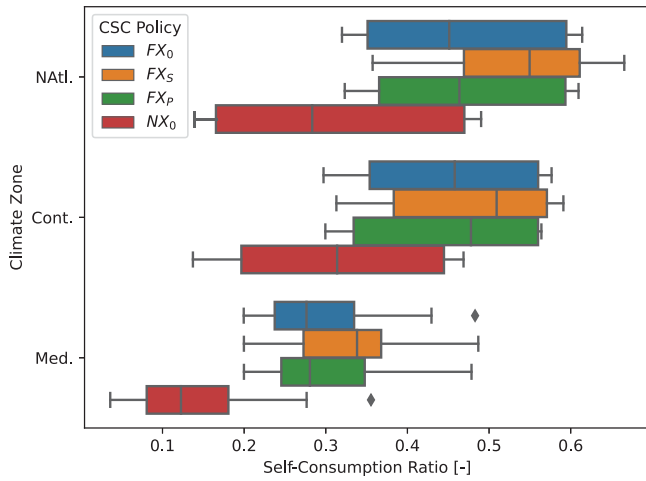


**Fig. C.7.** Statistical distribution of net present value to the building owners for CSC with heat in North Atlantic, Continental and Mediterranean climate for four CSC regulation variants. Black diamonds represent outliers.

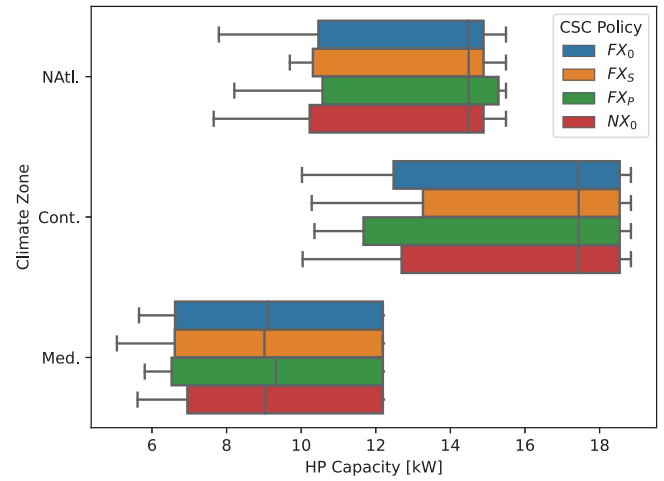


**Fig. C.8.** Statistical distribution of net present value to the renters for CSC with heat in North Atlantic, Continental and Mediterranean climate for four CSC regulation variants. Black diamonds represent outliers.

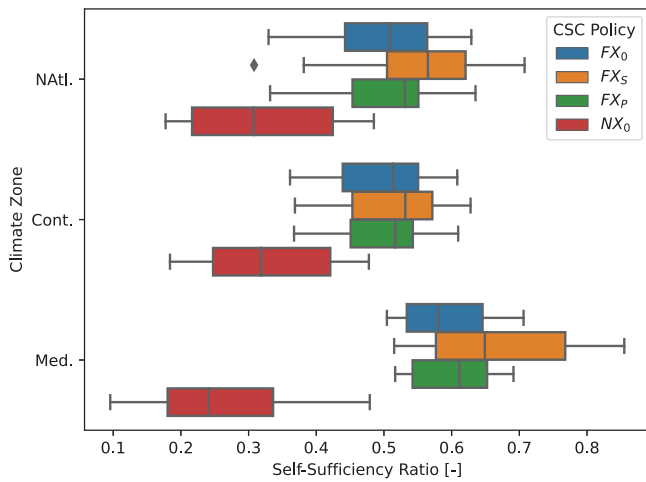




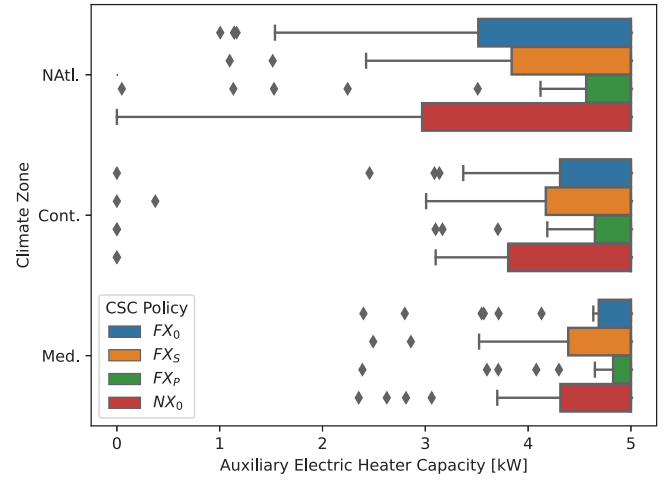
**Fig. C.9.** Statistical distribution of the self-consumption ratio for CSC with heat in North Atlantic, Continental and Mediterranean climate for four CSC regulation variants. Black diamonds represent outliers.



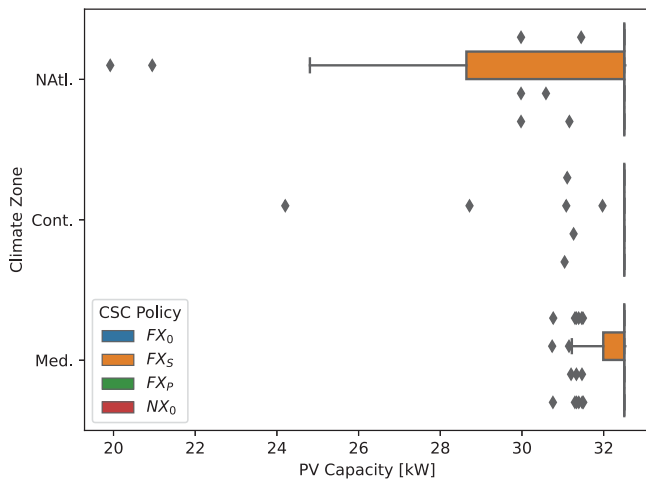
**Fig. C.12.** Statistical distribution of the installed heat pump capacity for CSC with heat in North Atlantic, Continental and Mediterranean climate for four CSC regulation variants.



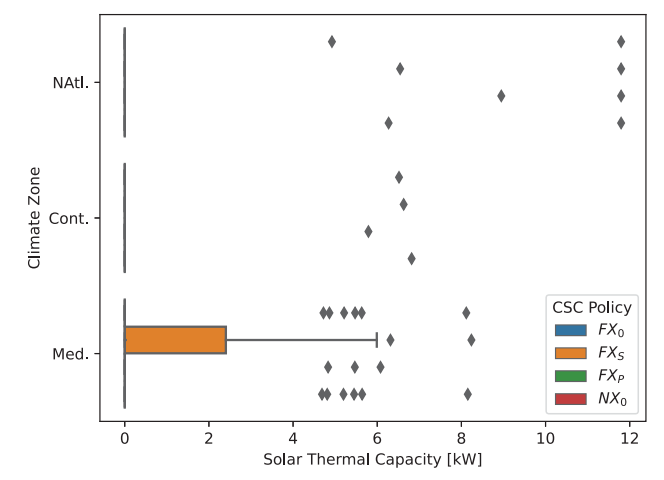
**Fig. C.10.** Statistical distribution of the self-sufficiency ratio for CSC with heat in North Atlantic, Continental and Mediterranean climate for four CSC regulation variants. Black diamonds represent outliers.



**Fig. C.13.** Statistical distribution of the installed electric heater capacity for CSC with heat in North Atlantic, Continental and Mediterranean climate for four CSC regulation variants. Black diamonds represent outliers.



**Fig. C.11.** Statistical distribution of the installed photovoltaics capacity for CSC with heat in North Atlantic, Continental and Mediterranean climate for four CSC regulation variants. Black diamonds represent outliers.



**Fig. C.14.** Statistical distribution of the installed solar thermal capacity for CSC with heat in North Atlantic, Continental and Mediterranean climate for four CSC regulation variants. Black diamonds represent outliers.

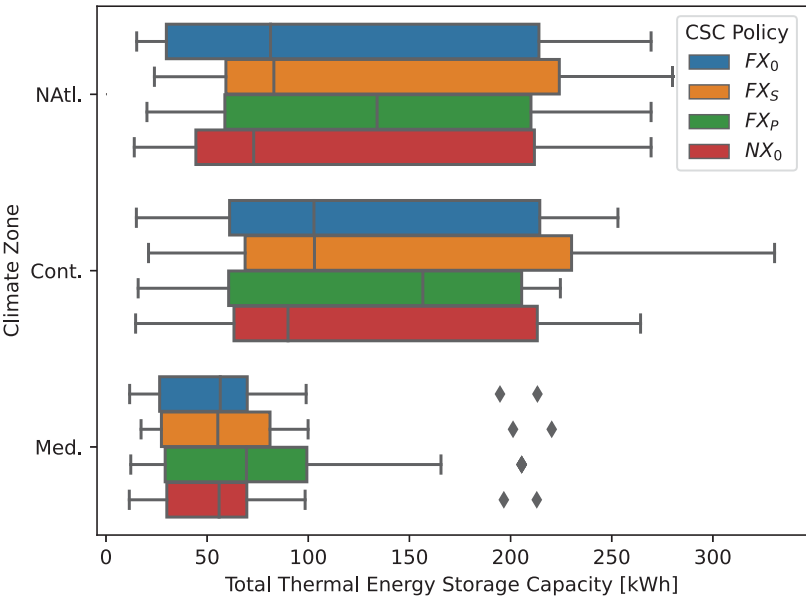


Fig. C.15. Statistical distribution of the total, i.e. domestic hot water and space heating, installed thermal energy storage capacity for CSC with heat in North Atlantic, Continental and Mediterranean climate for four CSC regulation variants. Black diamonds represent outliers.

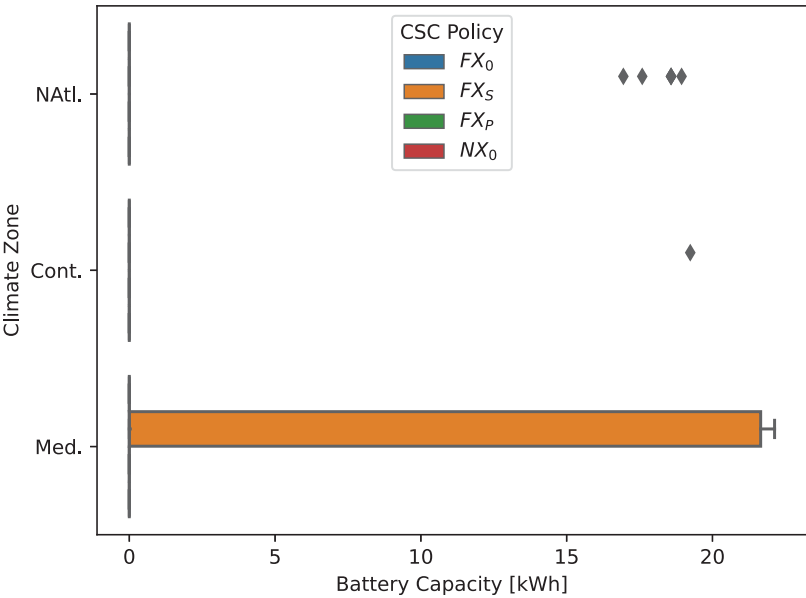


Fig. C.16. Statistical distribution of the installed battery capacity for CSC with heat in North Atlantic, Continental and Mediterranean climate for four CSC regulation variants. Black diamonds represent outliers.

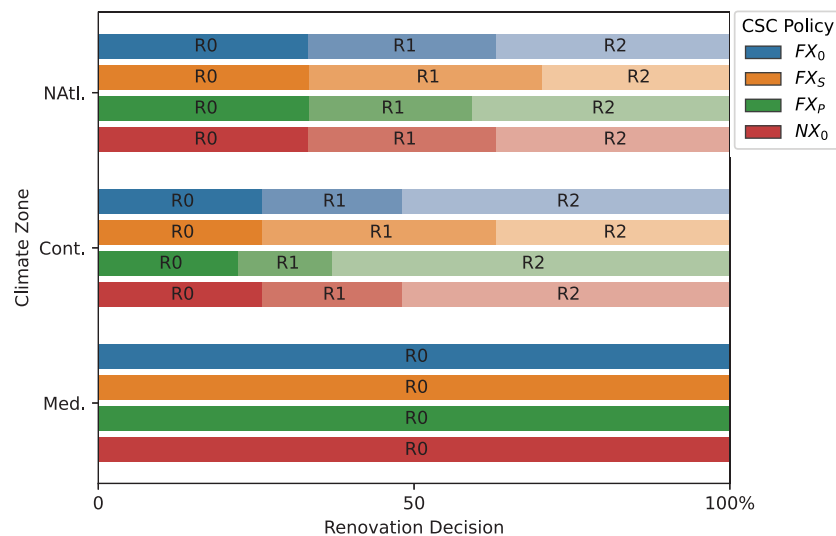


Fig. C.17. Percent occurrence of each passive retrofitting option for CSC with heat in North Atlantic, Continental and Mediterranean climate for four CSC regulation variants.

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