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Profitability of contracting business cases for shared photovoltaic generation and renovation measures in a residential multi-apartment building

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ABSTRACT

This study investigates the profitability of implementing active and passive building retrofitting measures, either individually or combined, within the framework of contracting. Three contracting models are investigated: (i) Photovoltaic (PV) contracting, (ii) renovation contracting, (iii) PV and renovation contracting including a heating system change. Since this study's practical approach focuses on the client (building owner), an optimisation model is developed that maximises the client's net present value, subject to a guaranteed pay-off including profit for the contractor. An algorithm allows to exactly quantify the impact of renovation measures on the heat load. The results show that PV system contracting is profitable for contractors and clients, while the profitability of passive retrofitting measures (e.g. building envelope renovation) significantly depends on the additional costs for CO_2 emissions as well as on the default heating system. The contracting framework itself decreases the profitability of retrofitting measures since the contractor as a third party awaits to gain profit as well. The significance of said impact depends heavily on the contractor's expected interest rate. In conclusion, in order to boost the shares of holistically retrofitted buildings (with or without PV integration), increasing costs for CO_2 emissions increase attractiveness for both the contractor, and the clients.

1. Introduction

In Europe, buildings account for approximately 40% of the total energy consumption, making them the largest energy consumers. This is not surprising when considering that 75% of the building stock is energy-inefficient, but only 0.4%–1.2% is retrofitted every year (European Commission, 2019b). Furthermore, the 2030 European climate goals (European Commission, 2019a), which propagate emission reductions, increasing shares of renewable energy and energy efficiency, underpin the necessity of thoroughly retrofitting the building stock, thus supporting increased renewable energy integration (mostly solar PV).

However, building owners have little incentive to invest in passive retrofitting measures[2] due to the significant upfront payments. In addition, despite strong evidence for the profitability of building-attached (and also partly building-integrated[3]) PV systems (active retrofitting), regulatory obstacles and organisational efforts hamper the increased and fast diffusion of active retrofitting measures in the multi-apartment building sector. A possible way to overcome these financial and organisational obstacles to conducting a thorough building retrofit is contracting. A contractor is an external agent who bears the initial investment as well as possible operation and maintenance costs. In turn, the client undertakes to reimburse the contractor in annual instalments, taking into account a certain interest rate to guarantee a profit for the contractor. The concept of contracting has already been previously established in the context of building renovation/retrofitting.

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[2] Passive retrofitting measures comprise improvements of the building envelope, such as insulation upgrades and replacing old windows with novel ones with thermal insulation glazing.

[3] Usually, building-integrated PV systems are less profitable than building-attached ones, since additional costs for basic renovations occur.

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However, contracting did not take hold on a large scale, mainly due to limited profitability of passive retrofitting.

So far, the scientific literature addresses the topics of (i) PV in buildings, (ii) building renovation and (iii) contracting separately. Therefore, the motivation of this work is to provide a holistic approach that allows to investigate the profitability of optimally sized PV systems, various renovation options and a heating system change in a residential multi-apartment building within the framework of contracting.

The approach used in this study[4] shifts the focus of the investigation onto the client,[5] since they are likely to refuse the services of a contractor unless the contractor's offer fulfils the client's (monetary) expectations. On the other hand, a certain profit must be guaranteed to the contractor, since otherwise they would refrain from offering their services. To that end, a mixed-integer linear optimisation model is developed to investigate the profitability of active and passive building retrofitting options with the objective of maximising the client's net present value (NPV). Simultaneously, the contractor NPV must be greater than or equal to zero. The contractor is guaranteed a certain profit by choosing an adequate interest rate. Three different contracting options are investigated: (i) PV system contracting, (ii) passive renovation contracting and (iii) a combination of PV system, passive renovation and heating system contracting. The cost-optimal PV and heating system capacities are endogenously determined by the optimisation model. Concerning the implementation of passive retrofitting measures, an algorithm is developed that maps the impact of various renovation measures in detail. The profitability of different active and passive retrofitting options can be determined by comparing the client NPVs before and after the implementation of retrofitting measures. Thus, various influencing factors on profitability such as the introduction of additional costs for CO_2 emissions, different interest rates for the contractor and different default settings of the building, are investigated.

The remainder of this paper is organised as follows. Section 2 provides an overview of the state of the art in the scientific literature. The model and the method are introduced in Section 3. The results are provided in Section 4. Section 5 draws the conclusion and suggests potential future research topics.

2. State of the art and progress beyond

According to the European 2030 climate goals, the share of renewable energy needs to be increased to at least 32%, the greenhouse gas emissions need to be cut by 40% (compared to the levels of 1990) and, the energy efficiency needs to be improved by 32.5% (European Commission, 2019a) .[6] Improvements in the building sector, such as increasing the building standard by passive retrofitting and increasing the share of renewable energy by PV implementation (active retrofitting), can contribute to achieving these targets.

However, passive building retrofitting poses a significant financial burden on the majority of building owners or owner communities, wherefore the renovation rate of buildings is low (European Commission, 2019b). Concerning active retrofitting, the implementation rate of PV systems in buildings is insignificant despite strong evidence for the profitability thereof (Roberts et al., 2019b, 2019c; Fina et al., 2018, 2019a, 2019b). A possible way to overcome the financial as well as organisational barriers of a thorough building retrofit is contracting.

Encompassing the topics of investigation in this paper, the literature review below focuses on the contributions in the following areas:

- PV sharing in buildings (Section 2.1),
- building retrofitting (Section 2.2), and
- energy/retrofit contracting (Section 2.3).

2.1. PV sharing in buildings

Due to legislative amendments in various European countries, the implementation of PV systems is no longer restricted to single-family buildings. Meanwhile, PV-sharing concepts can be implemented within multi-apartment buildings or even between multiple buildings. Shared PV generation can not only increase self-consumption but also adds customer value (Roberts et al., 2019b), while the effect of increased self-consumption and self-sufficiency can be enhanced by implementing battery storage. The added value of shared PV systems for customers in terms of cost savings is specifically addressed in (Fina et al., 2018) and (Fina et al., 2019b). Despite the available legal and regulatory framework to implement PV systems as well as the proven profitability and numerous other advantages, there are still barriers that hamper PV deployment. The scientific literature (Roberts et al., 2019a) juxtaposes a variety of opportunities for PV deployment with barriers (Zhang et al., 2015a). focuses on market barriers specifically, while still existing technical challenges are addressed in (Jamal et al., 2017). Deeper insights into the scientific literature of PV sharing are provided and summarised in (Fina et al., 2019b).

2.2. Retrofitting in buildings

Building retrofitting can be subdivided into purely passive retrofitting measures and a combination of active and passive retrofitting options.

2.2.1. Passive retrofitting

Conventional building renovation measures, such as insulation upgrades to the building envelope and installing higher quality windows, are referred to as passive retrofitting measures. Passive building renovation is often hampered by obstacles such as conflicting interests of landlords and tenants (Ástmarsson et al., 2013) or missing planning/evaluation tools and methods for sustainable building renovation (Jensen and Maslesa, 2015; Nielsen et al., 2016; Pombo et al., 2016; Ferreira et al., 2013). The latter is addressed in (Flourentzou and Roulet, 2002) by providing a systematic method to design appropriate renovation scenarios. Aiming at facilitating investment decisions as well (Dall'O' et al., 2012), describes an innovative approach to the analysis of the energy savings potential of retrofitting the building stock. The profitability of energy-efficient retrofit investments is analysed from the building owner's perspective and in context of the thus arising external benefits for society by (Amstalden et al., 2007) and (Friedman et al., 2014), respectively (Dodoo et al., 2017). presents a method for analysing the cost-effectiveness of energy saving measures, while (Jafari and Valentin, 2018) specifically studies the optimal selection of objectives for decision-making in building energy retrofits.

2.2.2. Active and passive retrofitting

Combined active and passive retrofitting measures are a combination of conventional renovation measures, such as insulation

[4] Another option to describe the interrelations of contractor and clients is game theory. However, game theory is more suitable for a theoretical approach. Since this study aims to provide an approach close to practice (business cases), it is explicitly refrained from using game theory.

[5] In this study, the term 'client' refers to an individual building owner as well as a community of owners or residents.

[6] According to the recent 'European Green Deal' developments, an increase of these numbers is highly probable.

and installing high-quality windows, complemented with novel heating systems and/or renewable energy integration. Multi-objective optimisation is used in the literature to optimally match renewable energy supply technologies and envelope retrofit in a residential community (Wu et al., 2017). The same optimisation approach is used to simultaneously maximise energy savings and minimise the payback period of retrofitting measures (Wang et al., 2014), and assist stakeholders in finding retrofitting measures that minimise the energy use in a cost-effective manner while satisfying the occupants' needs (Asadi et al., 2012). Focusing primarily on economic issues (Mauro et al., 2015), proposes a methodology for aiding cost-optimal retrofit of building categories. Profitability issues are further addressed by (Kumbaroğlu and Madlener, 2012), proposing a techno-economic evaluation method for finding the economically optimal set of retrofit measures, and by (Fina et al., 2019a), providing additional detail concerning cost-optimal dimensioning of different retrofitting measures. In order to illustrate the effectiveness thereof (Thomsen et al., 2016), provides an exemplary ex-ante/ex-post comparison in a residential building.

2.3. Contracting

To properly display a contracting situation in an optimisation model, two different ways can be chosen. On the one hand, there is the theoretical approach of contract theory. Contract theory is an agent-based approach that maps the interrelations of client and contractor and the contract bargaining process in detail. Such approach is suitable for the purpose of analysing very specific situations, which is not the goal of this work and thus out of scope of this article.[7] On the other hand, a less theoretical system analysis approach can be used. System analysis models rather focus on the practical situation of a contractor offering his services under specific conditions to which the clients agree in case their expectations are met in terms of energy service and building management. Thus, with respect to this article's scope, the following literature review focuses specifically on articles elaborating on energy and retrofit contracting.

2.3.1. Energy contracting

Due to the increased diffusion of renewable energy, energy market stakeholders may have to adapt their business models to remain competitive in the new energy landscape (Richter, 2012). Adequate contracting business models could be an option for utilities to stay competitive as well as facilitate residential investments in PV systems. Due to the increased importance of this subject matter, scientific literature that focuses on energy contracting has multiplied within the recent years. Respectively (Richter, 2012), and (Shang et al., 2017) provide a review of utilities' business models for renewable energy contracting as well as energy performance contracting (EPC) business models. By contrast (Pätäri and Sinkkonen, 2014), critically questions the viability of business models based on EPC offered by energy service companies (Wu et al., 2018). proposes a multi-criteria decision-making approach to investments in distributed PV projects under the EPC business model. The potential of said business model is rated in (Frangou et al., 2018). (Wu et al., 2018) focuses on third-party ownership models where solar service firms plan, install and maintain PV systems on the premises of a customer while using financing from a third party.

2.3.2. Retrofit contracting

Energy conservation is a challenging issue due to disincentives that inhibit innovation in the building sector (Hufen and de Bruijn, 2016). experimented with EPC that aims to replace disincentives with a stimulus for innovation. Similarly (Polzin et al., 2016), finds that barriers to retrofitting can be addressed by EPC, since outsourcing alleviates financial constraints. An EPC-based framework is proposed in (Zhang et al., 2015b) to enhance the profitability of 'green' investments by carefully sharing the existing risks (Faggianelli et al., 2017). provides a methodology for decision support of EPC with respect to risk associated with performance guarantee. Thus, EPC is one possible market mechanism to ensure building energy efficiency retrofit (Xu et al., 2015). The success factors are addressed in (Xu et al., 2011), while the risks and uncertainties in EPC projects are considered in (Lee et al., 2015) and (Qian and Guo, 2014). The contract period of EPC is one major factor influencing the success of such business models. Optimal EPC contract periods are addressed in (Deng et al., 2014; Lu et al., 2017; Shang et al., 2015).

2.4. Progress beyond the state of the art

Based on the literature review, this work clearly exhibits an advancement compared to previous studies. Concerning general energy contracting the literature is to a large extent purely theoretical (Richter, 2012, 2013; Shang et al., 2017; Pätäri and Sinkkonen, 2014; Strupeit et al., 2016). Literature that provides actual case studies mostly focuses on non-residential buildings such as hotels (Xu et al., 2015), office buildings (Faggianelli et al., 2017) and public buildings such as universities (Deng et al., 2014; Lu et al., 2017). Moreover, the majority of studies refrains from using optimisation techniques to determine, for example, optimal PV system sizes and/or other technical parameters of retrofitting. Regarding the literature on retrofit contracting, it is observed that the focus often lies on determining the optimal contract period (Deng et al., 2014; Lu et al., 2017) and/or the contract bargaining process (Shang et al., 2015). From a methodological point of view, this study explicitly refrains from using theoretical game theory, implementing an approach that is close to practice instead. Thus, the major contributions of this study can be summarised as follows:

This study investigates the profitability of thorough building retrofit by implementing active and passive retrofitting measures within the framework of contracting. Such a holistic approach, which covers the topics of PV in buildings, building renovation and contracting, is new and has not been studied yet. In order to also point out the differences of implementing individual retrofitting measures to holistic retrofitting, three different contracting approaches are considered: (i) PV contracting, (ii) renovation contracting and, (iii) a combination of PV and renovation contracting including a heating system change. An approach close to practice is used in order to illustrate the interrelations between the client and the contractor: An optimisation model is developed with the objective of maximising the client's net present value while simultaneously guaranteeing a profit for the contractor. Since this study aims at providing results that are close to reality, it is explicitly refrained from using theoretical game theory. Concerning passive retrofitting measures, an algorithm that calculates the impact of a variety of renovation measures on a building's heat load, is provided. Finally, a case study is provided for a multi-apartment building with ten residential units in order to highlight the impact

[7] However, a broad selection of scientific literature can be found that addresses various aspects of contracting in buildings in an agent-based way. To present a few examples, articles such as, Liang et al. (2016); Huimin et al. (2019); Liang et al. (2019); Ruparathna et al. (2017) , and focus explicitly on game theoretical and agent-based approaches to address retrofit decision making, energy performance contracting, energy-efficiency retrofit, and economic retrofit aspects, respectively. Further literature that focuses on game theoretical and agent-based approaches to address the general topic of PV sharing in buildings is provided in Fina et al. (2019b).

of retrofitting options and to determine whether the implementation of different contracting options results in monetary benefits for both the client, and the contractor. Since a broad selection of results is provided, this study simplifies the decision making process of building owners whether hiring a contractor results in monetary benefits under different circumstances.

3. Model and method

In this study, a model is developed that allows to determine the profitability of active and passive building retrofitting measures within the framework of contracting. The primary purpose of contracting is that the initial investment is made by a contractor, potentially offering financial relief to the building owner. In return, the building owner undertakes to make annual payments to cover the contractor's total expenditures (plus a certain profit) at the end of the contracting period. The contractor's expenditures comprise the investment as well as possible operation and maintenance costs. The annual payments by the building owner to the contractor are also referred to as 'contracting rate' (CR).

In the course of this paper, three different contracting models are examined.

- *Contracting option 1*: PV contracting
- *Contracting option 2:* Renovation contracting
- *Contracting option 3:* PV and renovation contracting including a heating system change

The first contracting option considers active building retrofit by implementing a rooftop PV system. The second option focuses on a variety of passive building retrofitting options such as building envelope insulation. The third and holistic contracting option combines active and passive retrofitting measures including a heating system change.

In order to realistically determine the profitability of building retrofitting measures within the framework of contracting, an optimisation model is developed that illustrates the interrelations between the client (the building owner or a community of owners) and the contractor on a practical level. Details of the optimisation model are given in Section 3.1. The determination of optimal PV and heating system capacities as well as the correct cost allocation depending on the contraction model of investigation is also addressed in the course of Section 3.1. Since a major part of this study addresses the implementation of different passive retrofitting (renovation) options, the impact of said renovation measures on the building heat load needs to be considered in detail. This is explained in Section 3.2. Results are provided for the case study of a multi-apartment building. The building set-up is specified in Section 3.3.

3.1. Optimisation model

When investigating the business case of building retrofit contracting, two major parties can be identified. First, there is the client who aims at improving the building's standard but has trouble affording the high upfront payment. Second, there is the contractor, who agrees to make the investment instead and in turn receives annual payments from the client to cover the expenditures (plus an additional profit). Therefore, the contractor and the client have similar objectives, namely to maximise their own financial positions.

Since the focus of this study lies on the profitability for the client, the optimisation problems' objective is to maximise the client NPV. The client NPV in it's general form is given in Equation (1). The nomenclature for this section is provided in Tables 3 and 4.

$$NPV_{clients} = -I_{0\_clients} + \sum_{y=1}^{Y} \frac{R_{clients}(y) - C_{clients}(y)}{(1 + r_{clients})^{y}} \tag{1}$$

However, in order to be able to guarantee the reimbursement of the contractor's expenditures including a certain profit, an according constraint needs to be set. To that end, the contractor NPV is calculated as well and is constrained to be greater than or equal to zero (Equation (2)). The contractor's profit is determined by the chosen interest rate. Since the optimisation objective is to maximise the client NPV, the contractor NPV is kept as close to zero as possible (with respect to the contractor's expected interest rate) in the optimisation process, because the greater the contractor NPV, the worse the client NPV becomes.

$$NPV_{contractor} = -I_{0\_contractor} + \sum_{y=1}^{Y} \frac{R_{contractor}(y) - C_{contractor}(y)}{(1 + r_{contractor})^{y}} \tag{2}$$

$$NPV_{contractor} \overset{!}{\geq} 0$$

Based on the contracting option chosen, costs are allocated appropriately to either the client or the contractor. A listing of all occurring costs, along with their calculations is provided in detail in Table 1. The allocation of costs according to the chosen contracting option is given in Table 2 .[8]

Further constraints to the optimisation model are necessary for covering the building's electricity and heat load at every point in time. Depending on the heating system implemented, the heat load (Equation (4)) can be covered by fossil fuels (gas or oil in the default setting) or if a heating system change is performed, by electricity from a heat pump.[9] Basically, the heat pump can be operated monovalently or bivalently. In case of a bivalent operation, the heat pump is supplemented by a heating rod that is operated by electricity from the grid. The heat pump itself can be fed by electricity generated by the PV system (if available) as well as by electricity from the grid.

$$\begin{aligned} h_{load}(t,y) &= e_{hp}(t,y) + e_{grid\_2hload}(t,y) + e_{oil}(t,y) + e_{gas}(t,y) \\ e_{hp}(t,y) &= COP(t,y) \cdot \left[\sum_{d} \left(e_{rpv\_2hp}(d,t,y) \right) + e_{grid\_2hp}(t,y) \right] \end{aligned} \tag{3}$$

The electric load can be covered by electricity generated by the PV system (if available) or by purchasing electricity from the public grid (Equation (4)).

$$e_{load}(t,y) = e_{grid\_2eload}(t,y) + \sum_{d} \left(e_{rpv\_2eload}(d,t,y) \right) \tag{4}$$

The total electricity generated by the rooftop PV system is determined by the installed capacity multiplied by the solar PV

[8] When PV contracting is analysed, all costs associated with PV (investment as well as operation and maintenance costs) are allocated to the contractor. The remaining costs are allocated to the client. However, cost terms such as investment costs for a heating system change or passive retrofitting would be zero in this example.

[9] This model also provides the option of investing in other heating options such as district heating or biomass heating. However, in this study, the focus lies on fossil heating options and heat pumps.

Table 1
Different cost items.

Cost item	Explanation	Calculation	Indication
Investment costs			
I_{0_rpv}	RPV investment costs	$i_{0\_rpv} \cdot \sum_d P_{rpv}(d)$	I_1
I_{0_hp}	Heat pump investment costs	$i_{0\_hp} \cdot Cap_{hp}$	I_2
I_{0_renov}	Investment in passive renovation measures	$i_{0\_win} \cdot n_{win} + i_{0\_insul\_out} \cdot A_{OW} + i_{0\_insul\_in} \cdot (A_{CFC} + A_{TFC} + A_{NW})$	I_3
Annual revenues			
$R_{rpv}(y)$	Revenues by surplus RPV feed-in into the grid	$\sum_t \sum_d e_{rpv2grid}(d,t,y) \cdot p_{feedin}(y)$	R_1
CR	Contracting rate (revenue from contractor view)	determined by optimisation	R_2
Annual costs			
$C_{Anno\_rpv}(y)$	Annual costs for RPV (operational cost, cleaning costs)	$c_{op\_rpv}(y) + c_{clean\_rpv}(y) \cdot \sum_d P_{rpv}(d)$	C_1
$C_{gridcons}(y)$	Costs for grid electricity purchase (electricity load coverage, feeding heat pump and heating rod)	$\sum_t (e_{grid\_2eload}(t,y) + e_{grid\_2hp}(t,y) + e_{grid\_2hload}(t,y)) \cdot p_{grid}(y)$	C_2
$C_{CO2}(y)$	Additional costs for CO_2 emissions	$\left(\sum_t h_{load}\left(t,y\right) \cdot f_{CO_2\_heat} + \sum_t \left(e_{grid\_2eload}\left(t,y\right) + e_{grid\_2hp}\left(t,y\right) + e_{grid\_2hload}\left(t,y\right)\right) \cdot f_{CO_2\_elec}\right)$	C_3
$C_{anno\_heatsys}(y)$	Fixed/maintenance cost of heating system	gas/oil: $c_{maint\_heat}(y) \cdot n_{units}$, heat pump: $c_{maint\_heat}(y)$	C_4
$C_{Anno\_else}(y)$	Additional annual costs - fixed costs for grid connection	$c_{fix\_elec}(y) \cdot n_{units}$	C_5
$C_{var\_heatsys}(y)$	Heating ‘fuel’ costs	$\sum_t h_{load}(t,y) \cdot p_{fuel}(y)$	C_6
CR	Contracting rate (costs from client view)	by optimisation	C_7

Table 2
Cost item allocation according to contracting model.

		Contractor	Client
Contracting Option 1	Investment	I_1	I_2,I_3
	Annual revenues	R_1,R_2	–
	Annual costs	C_1	C_2,C_3,C_4 C_5 C_6,C_7
Contracting Option 2	Investment	I_3	I_1,I_2
	Revenue	R_2	R_1
	Annual costs	–	C_1,C_2,C_3,C_4 C_5 C_6,C_7
Contracting Option 3	Investment	I_1,I_2,I_3	–
	Revenues	R_1,R_2	–
	Annual costs	C_1,C_4	C_2,C_3,C_5 C_6,C_7

generation in kWh/kW[10] (Equation (7)). Said electricity can be used to cover the electricity load and supply the heat pump. The surplus is fed into the grid. The optimal PV system capacity is determined endogenously in the optimisation process and is constrained by the maximum available roof space.

$$e_{rpv\_2eload}(d,t,y) + e_{rpv\_2hp}(d,t,y) + e_{rpv\_2grid}(d,t,y) = P_{rpv}(d) \cdot I(d,t,y) \quad (5)$$

All electricity and heat flows as well as the PV and heat pump capacity are optimisation variables; Their values are determined cost-optimal by optimisation. This means that in case PV system implementation were not profitable, the optimal PV capacity would be determined to be zero by optimisation.

The implementation of building renovation measures is modelled differently from PV and heating systems. As previously described, the optimal PV and heat pump capacities are determined by optimisation, which would not be conducive to passive retrofitting measures. When passive retrofitting measures are considered (as done in contracting options 2 and 3), it is simply assumed that the chosen renovation measures are implemented. Based on the chosen renovation measures, the building's heat load is reduced. Based on the improved building quality, the client NPV is again determined by optimisation. The newly calculated client NPV can then be compared to the client NPV that was determined before implementing any renovation measures (default NPV). If the newly calculated client NPV is higher than the default NPV, then the installed renovation measures are considered profitable.

The toolbox Yalmip (Löfberg, 2019) is used as the optimiser, Gurobi (Gurobi, 2019) as the solver.

3.2. Detailed heat load calculation and impact of retrofitting measures

As previously mentioned, the building's heat load and thus the impact of renovation measures on the heat load are modelled in detail, based on the specifications of the materials used. The nomenclature for this section is given in Table 5. In general, the heat load (P_H in kW) of a building is composed of transmission P_T and ventilation P_V heat load (Equation (6)).

$$P_H = P_T + P_V \quad (6)$$

The transmission heat load can be calculated as demonstrated in Equation (7).[11] The total transmission heat load is composed of the individual transmission heat loads of the individual building parts (x). The thermal conductivity (U_x) of each building part depends on the materials (specifications and thickness).

$$P_T = \sum_x U_x \cdot A_x \cdot (t_i - t_a) \cdot 10^{(-3)}, \text{ with } t_a \in t_{aN}, \ t_{aB}, \quad \text{with} \quad U_x = 1 \Big/ \left(\alpha_x + \sum_j b_j \Big/ \lambda_j\right) \quad (7)$$

The calculation of the ventilation heat load is shown in Equation

[10] Usually, the solar PV generation is given in kWh/m^2, but by introducing a transformation factor of 6 m^2/kW (a panel of 0.25 kW is assumed to have the size of 1.5 m^2), the irradiation can be converted to the unit kWh/kW.

[11] The factor $10^{(-3)}$ adjusts the unit W to kW.

Table 3
Nomenclature and costs.

Name	Explanation	Value/Unit
c_{clean_rpv}	Cleaning costs for rooftop PV	15EUR/kW
c_{fix_elec}	Fixed costs for grid connection	65EUR/yr
c_{maint_heat}	Fixed heating costs	gas: 150EUR/yr/unit, oil: 150EUR/yr/unit, heat pump: 300EUR/yr
c_{op_rpv}	Annual operational costs for rooftop PV	60EUR/yr
d	direction (North/South/East/West)	–
e_{gas}	Energy by gas heating	kWh
e_{grid_2eload}	Electricity from RPV to grid	kWh
e_{grid_2hload}	Electricity flow from grid to heating rod	kWh
e_{grid_2hp}	Electricity flow from grid to heat pump	kWh
e_{hp}	Electricity generated by heat pump	kWh
e_{load}	Building electric load	kWh
e_{oil}	Energy by oil heating	kWh
e_{rpv_2eload}	Rooftop PV electricity to cover the electricity load	kWh
e_{rpv_2grid}	Rooftop PV electricity fed to grid	kWh
e_{rpv_2hp}	Rooftop PV electricity to supply the heat pump	kWh
f_{A2P}	Transformation factor kilowatts (PV) ↔ square meters	$6m^2/kW$
$f_{CO_2\_elec}$	Transformation factor kg_{CO2} per kWh [a]	0.25kg/kWh
$f_{CO_2\_heat}$	Transformation factor kg_{CO2} per kWh[b]	Gas: 0.44kg/kWh, Oil: 0.645kg/kWh
h_{load}	Building heat load	kWh
i_{0_hp}	Specific investment costs for heat pump	1000EUR/kWh
$i_{0\_insul\_in}$	Specific costs for internal insulation with mineral wool[c]	$83EUR/m^2$
$i_{0\_insul\_out}$	Specific costs for external insulation with mineral wool	$106EUR/m^2$
i_{0_rpv}	Specific investment costs rooftop PV systems[d]	1050EUR/kW
i_{0_win}	Costs for one window	488EUR/piece

[a] The assumed CO_2 factor is valid for the Austrian electricity mix (Umweltbundesamt, 2017).
[b] The assumed CO_2 factors are in line with (E-Control, 2017).
[c] Costs for renovation measures are confirmed by (Maier, 2019).
[d] Costs for PV system installation are in line with (Frontini et al., 2015), taking into account further learning effects.

Table 4
Nomenclature and costs.

Name	Explanation	Value/Unit
n_{units}	Number of apartments	10
n_{win}	Number of windows	–
p_{CO_2}	Price for CO_2 emissions[a]	84.3EUR/t
p_{feedin}	Price for surplus PV feed-in	0.03EUR/kWh
p_{fuel}	Heating fuel costs[b]	Gas: 0.05EUR/kWh, Oil: 0.08EUR/kWh
p_{grid}	Price for electricity purchase from the grid[c]	0.22EUR/kWh
$r_{clients}$	Client's interest rate	3%
$r_{contractor}$	Contractor's interest rate	5%–15%
t	Time steps (35040 quarter hours per year)	–
y	Year	–
A_{CFC}	Cellar floor ceiling area	m^2
A_{NW}	Area of wall to neighbouring buildings	m^2
A_{OW}	Outer wall area	m^2
A_{TFC}	Top floor ceiling area	m^2
A_{facade}	Facade surface	m^2
Cap_{hp}	Optimal heat pump capacity (optimisation variable)	kW
$C_{clients}$	Client's annual costs	EUR/yr
$C_{contractor}$	Contractor's annual costs	EUR/yr
COP	Heat pump's coefficient of performance[d]	–
$I_{0\_clients}$	Investment costs borne by clients	EUR
$I_{0\_contractor}$	Investment costs borne by contractor	EUR
I	Solar PV generation	kWh/kW
$NPV_{clients}$	Client's net present value	EUR
$NPV_{contractor}$	Contractor's net present value	EUR
P_{rpv}	Optimal rooftop PV capacity (optimisation variable)	kW
$R_{clients}$	Client's annual revenues	EUR/yr
$R_{contractor}$	Contractor's annual revenues	EUR/yr
Y	Period of investigation, in years	20

[a] Future CO_2 prices are uncertain in general, for reasons of citability the assumed price is taken from (ENTSO-E, 2017).
[b] Costs for fossil fuels are in line with (Energieinstitut Vorarlberg, 2019).
[c] The Austrian retail energy prices depend on the supplier and the region. The chosen retail electricity price in this study is in line with data from the Austrian statistics institute 'Statistik Austria' (Statistik Austria, 2019).
[d] The COP depends on the outdoor temperature as well as the set-point indoor temperature, which is assumed to be 20° C. The lower the outdoor temperature, the smaller the heat pump's COP. A more detailed explanation is provided in (Fina et al., 2019a).

Table 5
Nomenclature and values.

Abbreviation	Specification	Value/ Unit
α_x	Heat transmission coefficient of building part x	m^2K/W
λ_j	Heat conductivitiy of material j	W/(mK)
ρ_{air}	Air density	1.3 kg/m^3
b_j	Thickness of material j	m
c_{hc}	Specific heat capacity	1.009kJ/ (kgK)
d	Direction (North/South/East/West)	–
f_{corr}	Solar irradiation reduction factor (shading by other buildings, trees, etc.)	5%
j	Material	–
n_{air}	Air exchange rate	0.21/h
n_{HD}	Heating days	
t_a	Outdoor temperature	° C
t_{aB}	Buffer room temperature	10° C
t_{aN}	Norm/standard outdoor temperature	−12° C
t_{diff}	Temperature difference	.. C
t_{daily_av}	Average daily temperature	° C
t_i	Indoor temperature	° C
x	Building part (e.g. outer wall, cellar floor ceiling etc.)	–
A_{MAB}	Multi-apartment building living area	m^2
$A_{windows}$	Total window surface	m^2
A_x	Surface of building part x	m^2
HDD	Heating degree days	Kd
E_{HL_spec}	Specific heat load	$kWh/m^2/$ yr
E_I	Internal gains	kWh
E_{in}	Solar irradiation	Wh/m^2
E_{net}	Theoretical net energy demand	kWh
E_S	Solar energy gains	kWh
G_I	Internal thermal gains	3 W/m^2
P_H	Total heat load	kW
P_V	Ventilation heat load	kW
P_T	Transmission heat load	kW
U_x	Thermal conductivity of building part x	$W/(m^2K)$
V_{MAB}	Building volume	m^3

Table 6
Building specifications, default setting.

Element	Description	Value[a]/Unit
Long building side	Yard and street side	17 m
Short building side	Adjoint to neighbouring buildings	12 m
Height of the building	Approx. 4 m per storey	20 m
Number of storeys	–	5
Number of windows	16 per storey (8 yard-, 8 street-side)	80

[a] The building dimensions are typical for multi-apartment buildings in the inner districts of Vienna, Austria.

(8) .[12]

$$P_V = (0.75 \cdot n_{air} \cdot \rho_{air} \cdot c_{hc} \cdot V_{MAB} \cdot (t_i - t_{aN})) / 3600 \tag{8}$$

After calculating the building heat load P_H, the theoretical net energy demand can be determined as shown in Equation (9) .[13]

$$E_{net} = P_H / (t_i - t_{aN}) \cdot HDD \cdot 24 \tag{9}$$

The heating degree days (HDD) are defined as the sum of the differences between the indoor temperature (assumed to be 20° C) and the daily outdoor temperature average across all heating days of a year. A day is considered a heating day if the average outdoor temperature falls below the heating limit, which is usually assumed to be 12° C. Thus, the HDD calculation can be formulated as demonstrated in Equation (10).

$$\begin{aligned} HDD &= \sum t_{diff} \quad \forall t_{diff} \le 8 \\ \text{with} \quad t_{diff} &= t_i - t_{daily\_av} \end{aligned} \tag{10}$$

In order to achieve a realistic value of a specific heat load (in $kWh/m^2/yr$), the net energy demand needs to be adjusted for two factors – solar gains and inside thermal gains. Depending on the orientation of the building (d - direction), solar gains through windows need to be considered (Equation (11) [14]). Inside thermal gains[15] can be considered to be 3 W/m^2. The total thermal gains are calculated as demonstrated in Equation (12) .[16]

$$E_S = \sum_d \sum_{t=1}^{35040} \left(E_{in}(d,t) \cdot 10^{(-3)}\right) \cdot f_{corr} \cdot A_{windows} \bigg/ 2 \tag{11}$$

$$E_I = \left(G_I \cdot 10^{(-3)} \cdot n_{HD} \cdot 24\right) \cdot A_{MAB} \tag{12}$$

After the net energy demand is adjusted for solar and internal thermal gains, the building's specific heat load in $kWh/m^2/yr$ can be calculated as demonstrated in Equation (13).

$$E_{HL\_spec} = (E_{net} - E_S - E_I) / A_{MAB} \tag{13}$$

Based on the specific heat load, the building's heat load profile, resolved at 15-min intervals, is determined as described in (Fina et al., 2019a).

3.3. Building set-up

In this study, the object of investigation is a five-storey multi-apartment building with ten residential units. This building is located in the city of Vienna, Austria, being directly adjoint to two neighbouring buildings. The building's roof is tilted at 30° and is oriented North-South. The building characteristics such as dimensions and construction materials, are specified in Table 6. The total building electricity load profile consists of ten individual, real-measured apartment load profiles, resolved at 15-min intervals. In the default setting[17], the building is heated by gas[18], and the specific heat load is determined to be approximately 140 $kWh/m^2/yr$. The heat load calculation[19] is based on the building's construction materials and their dimensions, which are listed in Tables 7 and 8.

3.4. Flow chart

Finally, a flow chart is given in Fig. 1 to graphically show the linkages between the different parts of the proposed methodology

[12] The factor 0.75 is the heat recovery factor. The factor 3600 implies the conversion from Joule, which equals Watt-Seconds, to Watt-Hours.
[13] The factor 24 implies the conversion of days (heating degree days (HDD)) to hours.
[14] The factor $10^{(-3)}$ adjusts the unit of the solar irradiation from Wh/m^2 to kWh/m^2.
[15] The inside thermal gains depend on the building utilisation (household, businesses or else) as well as on the number of people and electric appliances giving off heat. Since in this case a residential building is assumed, where the inhabitants are likely to work during the day, the internal gains are assumed to be on the lower end of the spectrum with 3 W/m^2, which is in line with Haas (2019) and Schramek (2007).
[16] The factor 24 implies the conversion to hours; $10^{(-3)}$ converts the original unit of the internal gains to kW/m^2.
[17] Default setting means that neither active nor passive retrofitting measures are implemented.
[18] Gas heating is typical for old multi-apartment buildings in city areas.
[19] The detailed calculation of a building's heat load is explained in Section 3.2.

Table 7
Building specifications, default setting.

Element	Material	Dimension[a]
Outer walls (yard and street side)	Limestone	0.02 m
	Brick	0.45 m
Outer walls (to neighbouring buildings)	Limestone	0.01 m
	Brick	0.3 m
Basement upper ceiling	Brick	0.45 m
Attic upper ceiling	Brick	0.45 m
Windows	Double windows, wood	1.1 × 1.8 m
Door	Wood	1.5 × 2.5 m

[a] The individual material dimensions are typical for central European buildings constructed around 1900.

Table 8
Material characteristics (Haas, 2019), default setting.

Characteristic	Material	Value
Thermal conductivity (U-Value)	Brick	0.85 W/(mK)
	Limestone	0.87 W/(mK)
Heat transfer coefficient (α)	Outer walls	0.17m^{2}K/W
	Intermediate floor (upwards)	0.25m^{2}K/W
	Intermediate floor (downwards)	0.34m^{2}K/W

and algorithms in Sections 3.1, 3.2 and 3.3.

4. Results

This section provides results for the previously introduced contracting options (i) PV contracting, (ii) renovation contracting and (iii) PV and renovation contracting including a heating system change.

- Section 4.1 addresses PV contracting. The results aim to provide an answer to the question whether PV systems are still profitable within the framework of a contracting business model where a third party – the contractor – expects to make a profit as well, which reduces the profitability of the installed technology for the building residents.
- Section 4.2 addresses the question whether building renovation, such as installing higher quality windows and upgrading the insulation, is actually not profitable or whether there are certain circumstances that help building renovation measures to break even.
- Section 4.3 addresses a holistic form of retrofit contracting, taking into account the possibility of PV system implementation, renovation and a heating system change. It is discussed under which circumstances a holistic building retrofit could be economically viable, even after changing the heating system from fairly cheap fossil fuels to a heat pump.

4.1. PV contracting

This section aims at determining whether installing a rooftop PV system within the framework of contracting is profitable for the client.[5] The cost-optimal PV system capacity is determined by optimisation. Therefore, the installed PV system capacity is an indicator for profitability. The more PV is installed, the higher the monetary value is. If PV system installation is not profitable, the optimal PV system capacity is set to zero in the optimisation process.

The profitability of PV systems within the framework of contracting is highly dependent on the contractor's expected return on investment. The contractor's expectations are reflected in the interest rate used to calculate the contractor's NPV.

Fig. 2 shows the impact of the contractor's interest rate on the optimal PV system size and the according client NPV[20]. The higher the contractor's interest rate, the less profitable PV installation becomes for the client, and consequently, the less PV is installed. At the same time, the client NPV decreases (worsens). Comparing the two extreme cases of a contractor's interest rate of 5% and 15%, it can be determined that the cost-optimal PV system capacities differ by 5.46 kW. This means that a 10% increase in the contractor's interest rate (from 5% to 15%) leads to a 63% reduction in the optimal PV system size. At the same time, however, the client NPV only worsens by 3.35%. This decrease might seem small at first; However, the positive financial impact of PV in this case study is limited to reducing the electricity grid consumption, while the client NPV considers all occurring costs within a time period of 20years, including the cost for heating. Moreover, the monetary benefits of a PV system with an installation capacity well below 10 kW for an entire multi-apartment building remain modest, as a matter of course.

The positive monetary impact of installing a PV system is higher without contracting. In this case, there is no third party, who also expects to make a profit from installing PV. In order to understand the monetary difference between these two situations (optimal PV installation with and without contractor), the client's NPV without contracting is visualised as a plane in Fig. 2. The according optimal PV system size rises to 10.57 kW.

4.1.1. Impact of CO_2 costs on PV contracting

This sensitivity analysis examines the effect of introducing additional CO_2 costs for electricity and heat to the results of PV contracting. A CO_2 price of 84.3EUR/t (ENTSO-E, 2017) is assumed[21]. Besides CO_2 costs, CO_2 factors of electricity and heat generation are needed as well. Since the multi-apartment building of investigation is located in Vienna, Austria, data is collected accordingly: The Austrian electricity generation mix causes CO_2 emissions of 0.25kg/kWh, according to the federal environment agency (Umweltbundesamt, 2017). The CO_2 factor of the building's default gas heating is assumed to be 0.44kg/kWh, which is in line with (E-Control, 2017).

The impact of CO_2 costs on the results for PV contracting is summarised in Table 9. The determined optimal PV system sizes increase, since purchasing electricity from the grid is more expensive if external costs, such as costs caused by CO_2 emissions, are internalised. However, the increase is modest and stays below 1 kW. By contrast, the client NPV difference is significant, since not only do the increased costs for purchasing grid electricity influence the client NPV, but especially the increased costs for heating with gas.

4.2. Renovation contracting

The second contracting option of investigation is renovation contracting. Renovation contracting can also be referred to as pure 'savings contracting', since it is not concerned with producing and self-consuming energy in contrast to PV contracting; It is solely focused on increasing the building standard and reducing the heat

[20] It needs to be remarked that the client NPV is always negative, since the NPV calculation considers (as introduced in Table 1) all costs within a time horizon of 20 years. If retrofitting measures are profitable, the client NPV increases (or in other words, the NPV 'becomes less negative'), but still remains negative as a matter of course.

[21] This exact number is assumed due to reasons of citability.

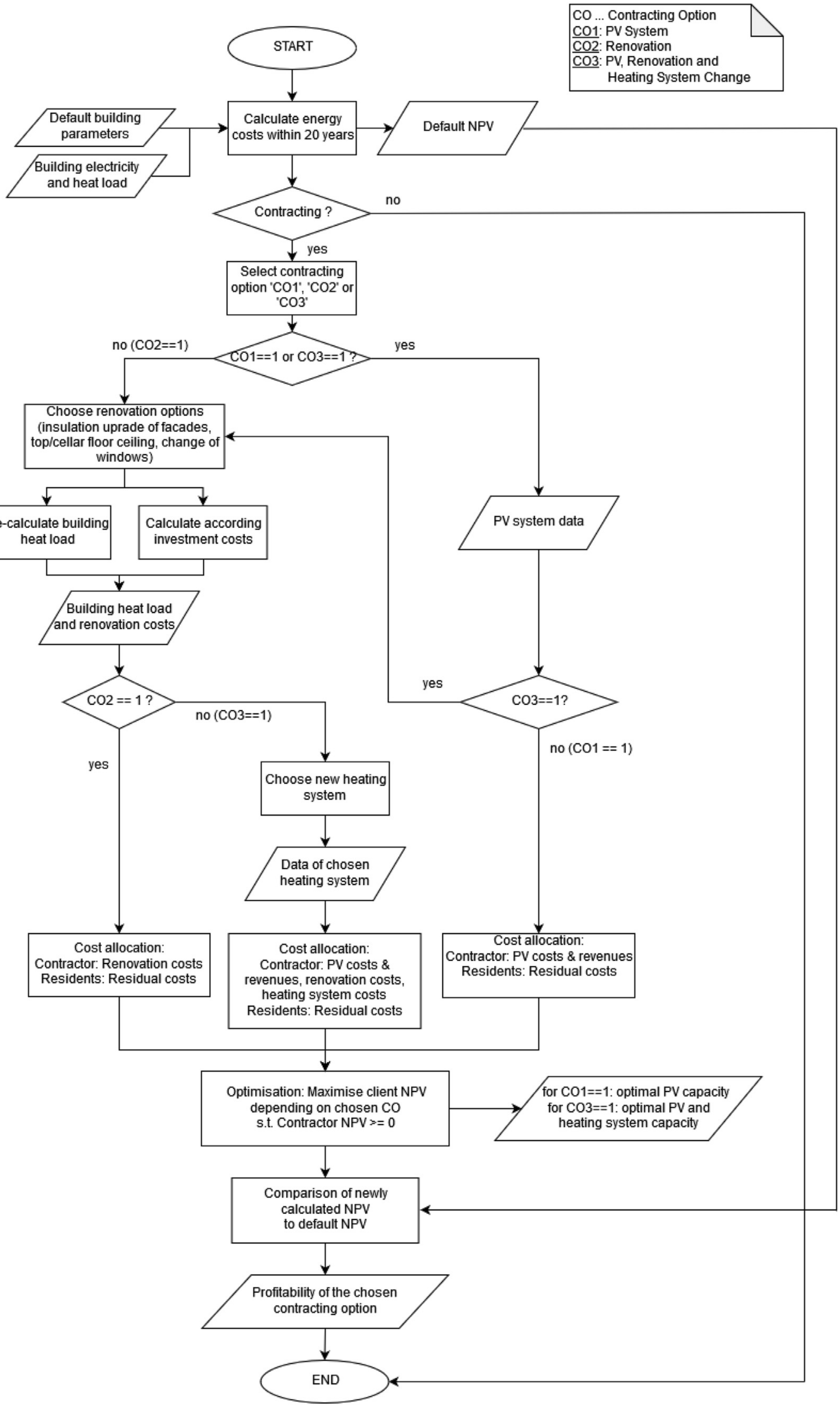

Fig. 1. Flow chart.

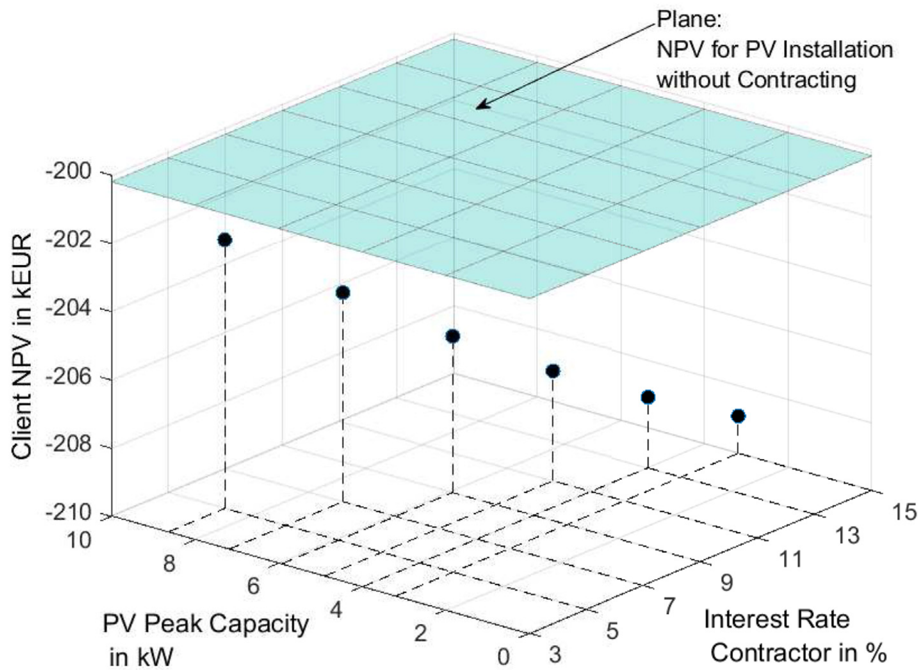

Fig. 2. Optimal PV capacity and client's NPV for a variety of contractor's interest rates.

Table 9
Result comparison of PV contracting with and without CO_2 costs.

Contractor's interest rate	Without CO_2 costs		With CO_2 costs		Differences	
	PV Capacity	NPV[20]	PV Capacity	NPV[20]	PV Capacity	NPV
	in kW	in kEUR	in kW	in kEUR	in kW	in kEUR
5%	8.65	−202.13	9.46	−276.67	0.81	74.54
7%	7.19	−203.87	7.97	−278.59	0.78	74.71
9%	5.93	−205.42	6.69	−280.32	0.76	74.90
11%	4.90	−206.77	5.61	−281.85	0.71	75.07
13%	3.99	−207.93	4.65	−283.19	0.66	75.25
15%	3.19	−208.91	3.86	−284.34	0.67	75.43

load. The most commonly implemented building renovation measures are installing higher quality windows and upgrading the insulation of the outer walls, the cellar floor ceiling, the top floor ceiling, and sometimes also the walls to the neighbouring buildings. Therefore, in this study, these five renovation measures are considered in the analyses and introduced in more detail in Table 10.

In order to properly assess the impact of building renovation measures, nine renovation options – including individual renovation measures as well as various combinations thereof – are introduced in Table 11. Depending on the renovation measures implemented, the building's heat load is reduced. If all renovation measures considered are implemented at once, the building quality increases to almost passive house standards with a heat load of only 21 kWh/m^2/yr[22]

The more significantly the heat load is reduced by the implementation of renovation measures, the better the impact on the environment (decreased CO_2 emissions, since the usage of the default gas heating is reduced). However, this also leads to higher investment costs. Whether the monetary value of annual energy cost savings (due to the reduced heat load) can compensate for the annual payments to the contractor is examined in the following.

In Fig. 3[23] the impact of different renovation options on the client NPV\ref{note4}s illustrated. Along with the decreasing heat load, the client NPV decreases as well (NPV worsens). It can be seen that the client NPVs calculated for the individual renovation possibilities (RC1 to RC9) are clearly below the default NPV that is calculated when no renovation measures are installed. The higher the monetary gap to the default NPV, the less profitable it is to implement the according renovation measures. This gap is indicated as 'subsidies needed for break-even' in Fig. 3, since governmental financial compensation would be necessary to incentivise the implementation of renovation measures.

The non-profitability of renovation contracting poses a big problem, since building owners have no incentive to increase the building standard if the monetary value of energy cost savings does not compensate for the annual payments to the contractor.

[22] For passive house standards, the heat load must not exceed 15 kWh/m^2/yr.

[23] The contractor's interest rate is assumed to be 7%, since the results in Section 4.1 have already shown that a high interest rate leads to a significant reduction in the profitability of retrofitting measures.

Table 10
Renovation measures specifications.

Renovation measure	Abbreviation	Specification	Costs[a]
Window change	WD	triple glazing and thermal-insulated frame, U-value = 0.6 W/m^{2}K	488EUR/piece
Insulation of top floor ceiling	TFC	16 cm of mineral wool, λ-value = 0.04 W/mK	83EUR/m^2
Insulation of cellar floor ceiling	CFC	16 cm of mineral wool, λ-value = 0.04 W/mK	83EUR/m^2
Insulation of outer wall	OW	16 cm of mineral wool, λ-value = 0.04 W/mK	106EUR/m^2
Insulation of wall to neighbouring building	NW	16 cm of mineral wool, λ-value = 0.04 W/mK	83EUR/m^2

[a] Realistic costs for individual renovation measures are provided by (Maier, 2019).

Table 11
Renovation measure combinations and their impact on the heat load.

Renovation Measure	Heat load in kWh/m^2/yr	Heat load reduction in kWh/m^2/yr	Code
No Renovation (default)	140.69	–	Default
TFC + CFC	119.35	21.33	RC1
WD	108.02	32.66	RC2
OW	94.31	46.37	RC3
WD + TFC	91.29	49.39	RC4
WD + TFC + CFC	86.69	53.99	RC5
WD + OW	61.65	79.04	RC6
WD + OW + TFC	44.92	95.77	RC7
WD + OW + TFC + CFC	40.32	100.37	RC8
WD + OW + NW + TFC + CFC	21.41	119.28	RC9

However, there are three major factors that impact the monetary value of building renovation in general.

1. The introduction of costs for CO_2 emissions affects the results. The significance of said impact is analysed in Section 4.2.1.
2. Another influencing factor, which is analysed in Section 4.2.2, is the framework of contracting itself, since not only do the building owner seeks a profit, but also the contractor as a third party.
3. Last but not least, the default setting of the building plays an important role. Depending on the default heating system installed and the according costs for heating, the positive impact of renovation measures varies. This is analysed in Section 4.2.3.

4.2.1. Impact of CO_2 costs on renovation contracting

Fossil heating systems account for a significant amount of CO_2 emissions in the building sector. This section analyses the impact of introducing CO_2 costs of 84.3EUR/t on the economic viability of renovation measures. [24] Since the default heating system of the building is gas, emissions of 0.44kg/kWh (E-Control, 2017) are assumed.

Fig. 4[23] compares the client NPVs[20]hen implementing different renovation options for the two cases with and without additional CO_2 costs. On the one hand, introducing costs for emissions reduces the client NPV in total, since the costs for heat and electricity rise significantly. On the other hand, it therefore becomes more valuable to reduce the building's heat load by implementing renovation measures. In other words, saving one kWh of heat load is significantly more valuable in the CO_2 costs scenario than it is in the case study without additional CO_2 costs. Therefore, when taking CO_2 costs into account, the monetary gap to the default NPV[25] is reduced and thus the number of subsidies that would be needed for renovation measures to break even shrinks. The number of subsidies needed to compensate for implementing renovation measures is depicted in Fig. 4, in percent of the default NPV ($NPV_{default}$ – client NPV before the implementation of any renovation measures) as given in Equation (14).

$$Subsidy = \left| \frac{\left(NPV_{default} - NPV_{renov}\right)}{NPV_{default}} \right|, \tag{14}$$

with NPV_{renov} being the client NPV after the implementation of renovation measures.

Interestingly, it can also be observed that the gap between the curves of the client NPV decreases with increasing building standards (RC1 towards RC9). This phenomenon can be explained as follows: Due to the high CO_2 costs, heat load reduction by renovation measures becomes more profitable: The positive monetary effect of avoiding CO_2 costs comes closer to compensating for the negative monetary effect of the annual payments to the contractor. This effect is the more pronounced, the more renovation measures are implemented, and consequently the more significantly the heat load is reduced.

4.2.2. Impact of the contracting business model on the profitability of renovation measures

Besides additional costs for CO_2 emissions, the contracting business model itself has an impact on the profitability of renovation measures, since the contractor expects a certain return on investment. These expectations are represented by the contractor's interest rate. Therefore, the profitability of renovation measures is expected to increase if the building owner/owner community refrains from assigning a contractor.

The blue and green bars in Fig. 5 indicate whether different renovation measures are economically viable if no contracting is applied by calculating the NPV difference[26] as given in Equation (15). These results are contrasted with the red bars, which show the client NPV difference if renovation measures are implemented within the framework of contracting (7% interest rate of the contractor.)

$$NPV_{diff} = NPV_{renov} - NPV_{default} \tag{15}$$

If the client NPV in the default setting[27] ($NPV_{default}$) is less negative than the client NPV after implementing renovation measures (NPV_{renov}), it would be more profitable to refrain from implementing renovation measures, since the monetary value of annual energy savings does not compensate for the initial

[24] Previous analyses showed that passive retrofitting measures per se do not break even within the assumed time horizon of 20 years. This means that the monetary value of energy savings achieved by implementing passive retrofitting measures does not compensate for the initial investment. However, when starting to internalise external costs, such as costs for CO_2 emissions, passive retrofitting measures might break even or, at least, the profitability gap towards the break-even point can be reduced.

[25] Depending on the case study, the default NPV differs whether additional CO_2 prices are taken into consideration or not.

[26] The NPV difference can also be seen as the profitability gap towards break-even.

[27] Default setting of the blue-bar scenario: gas heating, no additional CO_2 costs. Default setting of the green-bar scenario: gas heating, additional CO_2 costs. Default setting of the red-bar scenario: gas heating, no additional CO_2 costs.

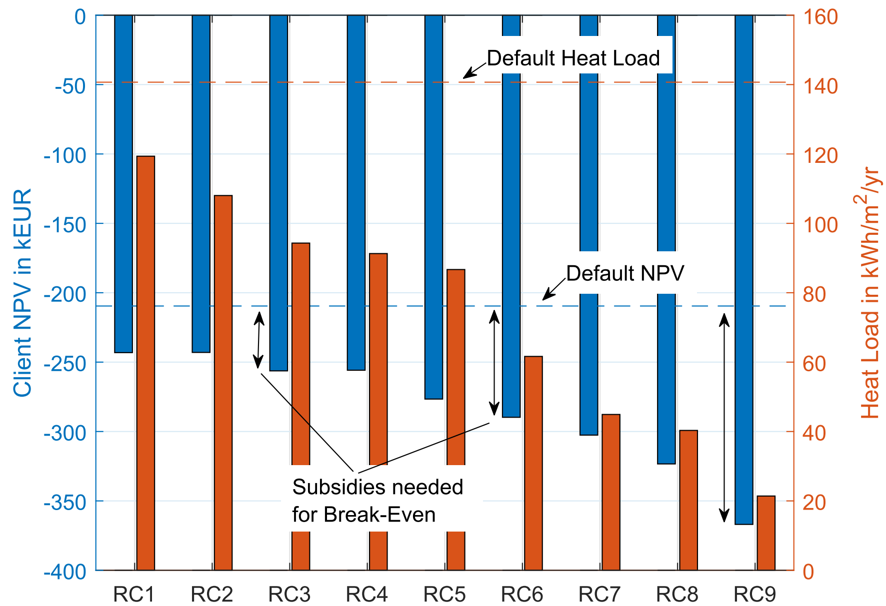

Fig. 3. Impact of renovation measures on the client NPV and the heat load. The contractor's interest rate is assumed to be 7%.

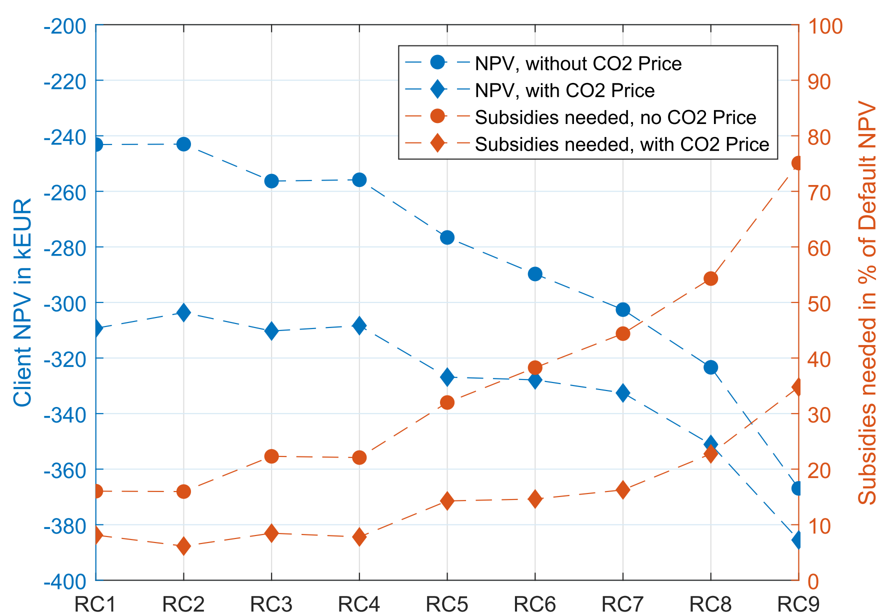

Fig. 4. Client NPV and subsidies needed in % of the default NPV. Heating system: Gas. Contractor interest rate: 7%.

investment. In such cases, the determined NPV difference NPV_{diff} is negative.

The actual impact of the contracting framework, with a contractor's interest rate of 7%, can be derived from the significant difference between the red and blue bars. The profitability gap when no contracting is applied (blue bars) is almost half as big compared to when contracting is applied (red bars). If additional costs for CO_2 emissions are introduced, renovation options such as RC2, RC3 and RC7 do almost break-even, while RC4 even achieves a positive NPV difference. This means that investing in higher quality

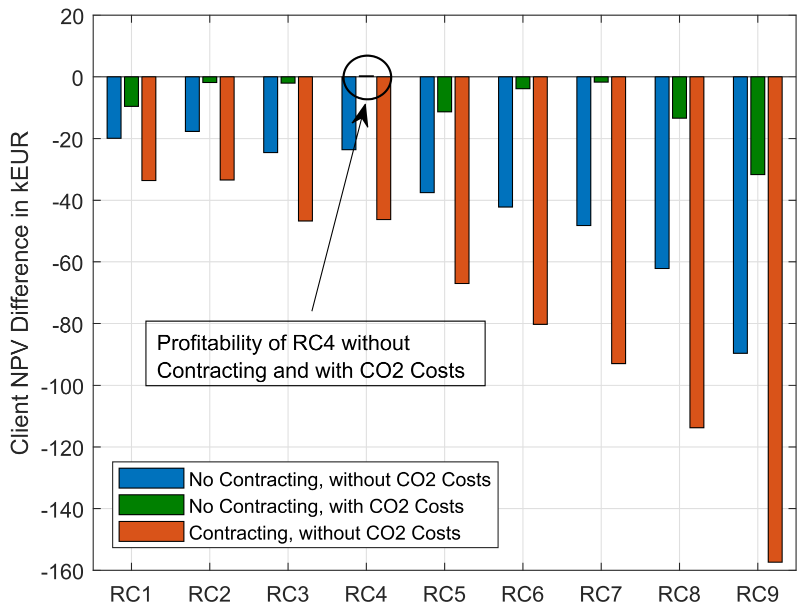

Fig. 5. Client NPV differences in case studies with and without contracting. In the case of contracting, the contracting interest rate is assumed with 7%.

windows and top floor ceiling insulation is actually profitable if additional costs for CO_2 emissions are introduced and the building owners do not assign a contractor.

4.2.3. Impact of oil heating systems

Up to this point, the multi-apartment building has been assumed to be heated with gas as the default setting. In this section, the default heating system is changed to oil. This assumption is justified because at present there are still many oil heating systems implemented in Austria, which have to be replaced as soon as possible[28]. Oil is an energy carrier that is more expensive (0.08EUR/kWh) than gas and causes higher CO_2 emissions (0.645kg/kWh).

Fig. 6[23] shows results that are equivalent to those in Section 4.2.1, with oil heating instead of gas heating as the only difference. This supposedly small change in the default setting[25] has a significant impact. Renovation measures break even more easily since heat load reduction is more valuable, from an economic point of view, the higher the costs for the energy carrier and emissions. In the case of oil heating as the default heating system and additional costs for CO_2 emissions, five out of nine renovation measures break even.

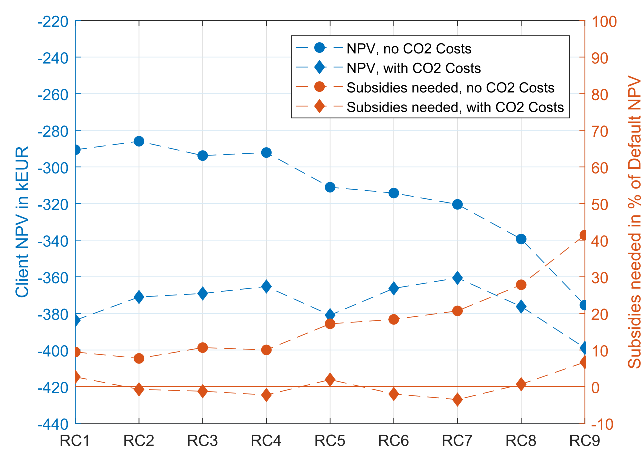

Fig. 6. Client NPV and subsidies needed in % of the default NPV. Heating system: Oil. Contractor interest rate: 7%.

4.3. PV, renovation and heating system contracting

The most holistic approach to contracting takes into account PV system installation, passive retrofitting measures as well as a heating system change. The latter investigates a change from the default gas heating to a bivalent heat pump that is supplemented by a heating rod. The cost-optimal heat pump capacity is determined by optimisation.

Since the heat pump can not only be supplied by electricity from the grid but also by electricity generated by the PV system, the optimal PV system size changes with the implementation of a heat pump. Going back to pure PV contracting, Table 9 shows an optimal PV system size of 7.19 kW (no additional CO_2 costs; contractor interest rate of 7%). In the event that all specifications are left unchanged, while the gas heating is replaced with a bivalent heat pump, the determined optimal PV system size rises to 10.34 kW.

Fig. 7 shows results of the holistic contracting approach for three different versions of the contractor's interest rate. The following observations can be made:

[28] In some parts of Austria, the installation of oil boilers is not only prohibited in new buildings, but also oil heating systems in the existing building stock may not be renewed anymore and need to be replaced with other heating options.

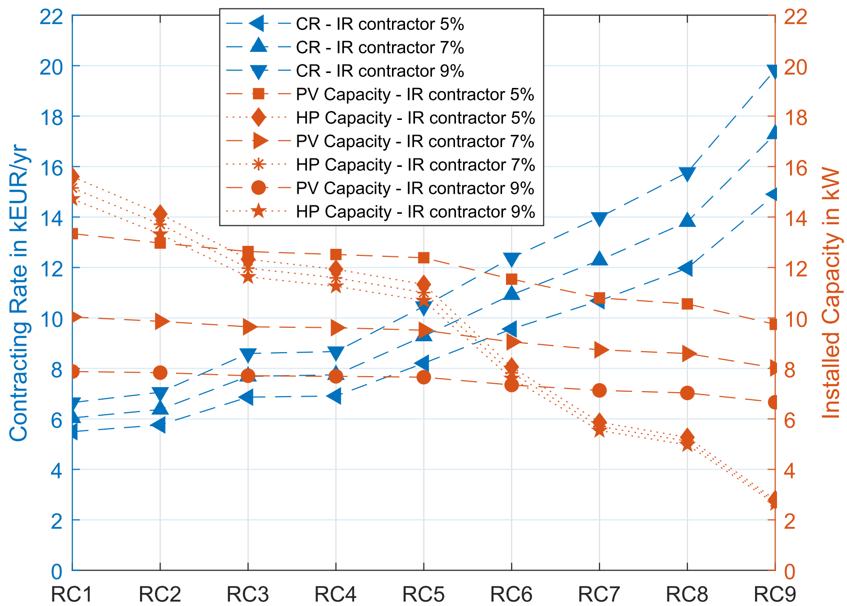

Fig. 7. Amount of contracting rate and optimal PV/heat pump capacities for different contractor interest rates.

- The higher the improvement of the building quality, the smaller the optimal heat pump size becomes. If the heat load is reduced to 21.41 kW (RC9), a heat pump capacity below 3 kW is cost-optimal[29]
- Since optimal PV system sizes correlate with the optimal heat pump capacities, the PV system capacities also shrink with the installed heat pump capacity.
- The decrease in optimal PV system sizes, however, is far less significant than the decrease in heat pump capacities with improved building quality. The reason is that the majority of PV electricity generation is still used for covering the electric load rather than feeding the heat pump, since heat demand and PV electricity generation are anti-correlated.[30]
- The contracting rates (annual payments to the contractor) increase from RC1 to RC9, despite the shrinking capacities of PV and heat pump. This emphasises the comparably small impact of the investment costs for PV and a heat pump in comparison to the investment costs for passive retrofitting measures, which clearly dominate the total investment costs and thus the contracting rate.

The results in this paper have so far shown that the profitability of retrofitting measures in general significantly depends on the contractor's interest rate and the costs of CO_2 emissions. The smallest possible interest rate of 5% is used for the final analysis as illustrated in Fig. 8. Additional costs for CO_2 emissions are also considered. On the one hand, the client NPVs are calculated for a holistic building retrofit (PV system, renovation measures and a heating system change). These NPVs are contrasted with two different default settings: (i) gas heating plus CO_2 costs and (ii) oil heating plus CO_2 costs. The client NPV of the default setting with an oil heating system lies significantly below (or in other words: is significantly more negative than) the client NPVs after holistic retrofitting. This means that holistic retrofitting is profitable if additional costs for CO_2 emissions are taken into account and oil heating is assumed to be the default heating system. Therefore, the NPV difference that is also shown in Fig. 8 is positive in this case (light blue bars). If the default heating system is gas, holistic retrofitting does not break even. This is illustrated by the dark blue bars, which show a negative NPV difference ($NPV_{diff} = NPV_{renov} - NPV_{default}$).

5. Conclusion and outlook

This study's approach that provides an alternative to purely theoretical game theoretical modeling, has proven to be suitable for determining the profitability of different retrofitting options within the framework of contracting. The focus is on the client (building owner), since it is primarily their monetary expectations that need to be fulfilled. At the same time, a certain profit is guaranteed for the contractor to reflect a realistic market situation. The model provides interesting results that show the actual impact of (i) the contracting framework itself, (ii) the contractor's interest rate, (iii) the building's default setting, and (iv) external conditions such as additional CO_2 costs on the profitability of different retrofitting measures.

The system analysis modelling approach provides results that are valid for a variety of different situations, which can be of help in the decision making process for building owners whether hiring a contractor is economically viable. However, this approach does not display the details of a possible bargaining process between the participating parties, since strictly rational decision making is assumed. This can be considered a limitation of the proposed approach. To gain results that illustrate the detailed interrelations of a contractor-client relationship and in this context address he problem of possible assymetric information distribution between

[29] The residual load is covered by the heating rod.

[30] In times of high PV generation (summer), the heat demand is low or even zero. In times of low PV generation (winter), the heat demand is high.

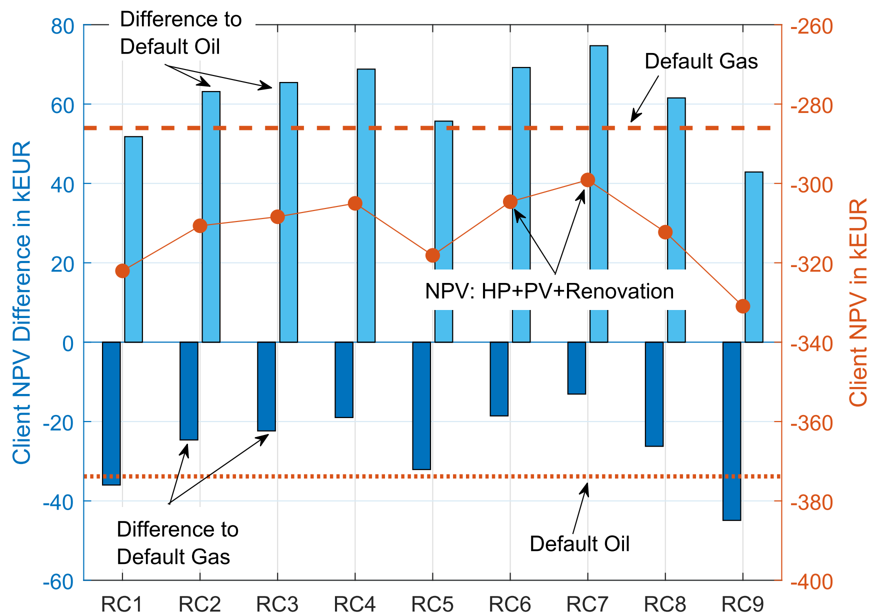

Fig. 8. Profitability of holistic retrofitting in the context of two different default settings (gas/oil heating). Contracting rate: 5%. Additional costs for CO_2 emissions included.

clients and contractor, contract theory as an agent-based modelling approach would need to be applied. A further limitation of this model is that the factor of uncertainty is not addressed. Since building retrofit contracting stretches over multiple years, encompassing risks associated with the long time horizon would increase the quality of results. Lastly, the introduced model is a mixed-integer linear optimisation which can only approximate non-linear relations.

Generally, building retrofit offers multiple options to positively influence the climate change: Active retrofitting measures such as PV system implementation lead to an increased deployment of renewables in the building sector and thus mitigate the need for conventional electricity. Replacing fossil heating systems or implementing passive renovation measures such as insulation upgrades and installing higher quality windows leads to significant improvements of a building's CO_2 balance. However, at present, the rate of building retrofits is insignificant, not least due to the high upfront costs. Contracting indeed solves the problem of bearing high upfront costs, but the profitability of implementing active and/or passive retrofitting measures is reduced at the same time, since the contractor expects a certain return on investment. The results have shown that the more conservative the contractor's profit expectations (the lower the assumed interest rate) are, the smaller the negative effect on the retrofitting measures' profitability is.

The contracting model of pure renovation contracting has not taken hold yet due to a lack of profitability, which is also confirmed by the results achieved in this study. However, the new developments in PV electricity generation in buildings lead to an increase in profitability of holistic building retrofit, since PV implementation is actually profitable. Moreover, a regulatory implementation of additional costs for CO_2 emissions can be expected in the near future, at least in Europe. The results show that this step would have a significant impact on the profitability of building retrofitting. By introducing CO_2 costs, even originally highly non-profitable options such as pure renovation contracting would eventually break even without additional subsidies, or, at least the knock-on financing could be reduced. Moreover, not only additional costs for CO_2 emissions are expected in the future, but also changes in the general structure of energy prices and PV system costs. Due to increased technological learning triggered by increasing PV installation shares, PV system costs are expected to decrease. Therefore, the economic viability of PV system installation itself and holistic building retrofit is expected to increase. On the contrary, a possible adaptation of future retail electricity prices could bring a reduction of per-unit prices while simultaneously increasing the fixed part of the electricity bill. Such development might hamper the implementation of building retrofit, since the savings in the electricity bill decrease due to reduced per-unit costs for grid electricity purchase. In case of a simultaneous decrease in PV system costs and per-unit retail electricity prices, the individual effects on profitability of retrofitting could, more or less, cancel each other out.

In addition to the introduction of external measures such as additional CO_2 costs, the default setting of the building has also proven to be crucial. Consequently, the following suggestions for future work can be derived: In this study, the object of investigation is a purely residential building. Future work should focus on the profitability of retrofitting measures in buildings that also accommodate businesses. Due to the significantly higher electricity and heat loads of businesses, an increase in the profitability of retrofitting measures is expected, since energy-saving measures become more valuable. Moreover, the focus of future work should not only lie on the electricity and heat demand but also on cooling in buildings. The cooling demand increases with the progression of climate change, which would increase the profitability of implementing PV systems in buildings. This increase needs to be quantified to exactly estimate the potential thereof. Finally, going a step further, the impact of implementing building retrofitting measures on a medium or large scale (district-, city- or even country-level) needs to be evaluated. The results might encourage policy makers to decide on reasonable levels of support for building retrofit.

Author declaration

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Declaration of competing interest

None.

CRediT authorship contribution statement

Bernadette Fina: Conceptualization, Methodology, Software, Validation, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Hans Auer:** Conceptualization, Validation, Writing - review & editing, Supervision. **Werner Friedl:** Validation, Supervision.

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