Analysis of Financial Benefits for Energy Retrofits of Owner-occupied Single-family Houses in Germany

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Abstract: *In many industrialized countries, a significant number of buildings were constructed prior to any energy-related building construction standards. Today, single-family houses (SFH/ pl. SFHs) from this time still have a comparably poor thermal quality. This paper aims to examine and model the incentive effects of the German energy retrofit funding schemes for owners of SFHs constructed shortly before the introduction of the first German thermal insulation ordinance in 1979. We develop a novel mixed-integer economic optimization model that determines the financially optimal energy retrofit configuration for owner-occupied SFHs. In a case study, we consider German framework conditions such as governmental incentives, standards, regulations, retrofit costs, and energy prices. We calculate economic burdens and benefits in 48 different retrofit scenarios for two representative SFHs constructed in the 1960s and 1970s. In the majority of cases, the return on investment is positive. For heating system retrofits, energy savings are comparatively small, but the cost-benefit ratios of retrofits are better than for measures on the building envelope. Overall, we find retrofits to decrease operational costs to between 15% and 62% of the initial value. The financial incentive effect of the German funding instruments can lead to financially optimal savings of CO_2 emissions in the range of 82-94%, however our findings show that the conditions of the German funding programs are not designed to maximize CO_2 savings per funded euro. We show that the funding invested to reduce the annual tons of CO_2 ranges from 493 € to 3,747 € in our case study.*

Key words: buildings, single-family houses, energy retrofits, financial incentives, optimization models, energy policy

Highlights:

- Economic optimization model for energy retrofit measures for single-family houses

- Case study of German buildings shows positive return on investment for most retrofits
- The funding invested to reduce the annual tons of CO_2 ranges from 493 € up to 3,747 €
- Public financial retrofit incentives minimize energy demand but not CO_2 emissions
- The approach is transferable to buildings and framework conditions in other countries

1 Introduction

In the European Union (EU), building stock accounts for roughly 40% of the final energy consumption, and roughly 36% of CO_2 emissions [1]. Thus, the reduction of buildings energy demands is a key element in the climate protection strategy of the EU to be implemented by Member States [2]. The German Government has declared its aim to reach an almost climate-neutral building stock by 2050. Specifically, the primary energy demand of buildings should be reduced by 80% compared to 2008 through energy savings and renewable energy supply [3]. Due to the low deconstruction and replacement rates and an increasing demand for residential area per capita [4], high energy standards for new buildings are not enough to reduce the energy demand of the building stock. Instead, retrofits of buildings with low energy standards are important. As in the rest of the EU, the retrofit rate in Germany has stagnated at around 1% per year [5-6], and the retrofit of building components or technical building equipment typically only takes place at least 30 years after installation [7]. Even for heating systems with a significantly shorter lifetime, experts usually expect its retrofit only 30 years after its installation [8]. To achieve the German climate goals for the building stock by 2050, it is crucial to accelerate retrofits, especially those with significant primary energy and CO_2 savings.

For many years, international research has given relatively little attention to retrofit strategies for single-family houses (SFH/ pl. SFHs). Lately, this has increased following the political interest due to the large potential for energy and CO_2 savings in many countries, especially in Europe [9-11]. In Germany, SFHs account for more than half of the residential building stock [12]. Of these, 87% are occupied by their owners and only 13% are rented [13]. About two thirds of the SFHs in Germany were built before the first German Heat Insulation Ordinance (Wärmeschutzverordnung) in 1979 and about one third was built between 1958 and 1978 with an often low energy quality [12,14]. Even today, about 50 years after their construction, their energy quality is significantly worse than that of newer buildings because of various deficits in their building envelopes and technical equipment. Their heating systems especially require energy retrofits [15].

In Germany, financial profitability appears to be a main driver for energy retrofits. This is highlighted by various studies by Stieß et al. (2010) [16], Gossen and Nischan (2014) [17] and Renz and Hacke (2016) [18] evaluating the motivations of energy retrofit clients via qualitative interviews and surveys. In all three studies, economic reasons such as a long-term reduction in energy costs, the reduction of operating costs, and short amortization periods were mentioned by almost all participants as major motivating factors for their energy retrofits.

To increase the economic incentives of energy retrofits, there are a variety of funding instruments for retrofitters in Germany. The largest and most popular funding programs for residential buildings are coordinated by the Kreditanstalt für Wiederaufbau (KfW), which is a public German banking group [19-21]. The funding programs "Energy Efficient Retrofit" and "Energy Efficient Building" for the period between 2005 and 2017 supported energy retrofit measures of about 2.8 million residential units. In total, 73 million € was invested, contributing to annual CO_2 savings of more than seven million tons [22-23]. Moreover, other smaller funding programs at the federal level are provided by the Bundesamt für Wirtschaft und Ausfuhrkontrolle (BAFA), the Federal Office for Economics and Export Control [3]. The BAFA funds particularly innovative heating systems with renewable energies [24]. Runst (2016) [25] analyzed the financial incentives of KfW and BAFA for energy retrofits of buildings for building oners. He summarized publications on payback periods for energy-related building retrofits and found that retrofit measures are in general not profitable for building owners despite KfW and BAFA funding. In 2020, the conditions of the KfW and BAFA funding system were updated and new tax advantages for energy retrofits of owner-occupied SFHs were introduced [26]. No studies are known to the authors providing information about the recent incentive effects of the German funding system since 2020 for climate-friendly retrofits from the financial perspective of self-using SFH owners.

Other European countries (e.g. Italy, Greece, UK, Ireland, Cyprus) provide similar financial incentives as part of their national building retrofit strategies [2]. As in Germany, these incentives have different forms such as funding schemes, grants and tax exemptions, or reductions that directly and indirectly reduce the retrofit costs to stimulate energy efficiency retrofits in residential and non-residential buildings [27-28]. Due to their high relevance and large investments from the public treasury, there are a variety of European studies investigating the best design of such funding instruments. The studies deal with, for example, regional and building specific differences for the funding design of a country [29-30], the comparison of different financial initiatives among selected European countries [28], the financial attractiveness of investments in the presence and absence of incentive schemes for building retrofits [27], and building owner preferences for different structures of financial incentives [31].

This study investigates the incentive effect of the German funding system of 2020 on the comprehensive energy retrofit of owner-occupied SFHs constructed between 1958 and 1978. Moreover, we analyse how much CO_2 can be saved with a financially optimal retrofit of these buildings from the perspective of the owners. For this, we develop an economic optimization model that provides information on the maximum possible financial savings of a building retrofit from the perspective of a self-using SFH owner.

Many existing models for energy retrofits of residential buildings focus on optimizing retrofit measures. Wang et al. (2014) [32] present an optimization model with a differential evolution algorithm to identify optimal retrofit measures that maximize both energy savings and economic benefits during a selected time period and with a fixed available budget. Kumbaroğlu and Madlener (2012) [33] develop an optimization model with a techno-economic evaluation method for the energy retrofit of buildings to find the optimal set of retrofit measures with maximum net present value for a case study building. Financial incentives for building owners and users are also considered to evaluate investment alternatives. Ruparathna et al. (2017) [34] propose a fuzzy logic-based life cycle cost analysis approach for building energy retrofits to estimate the overall costs of energy retrofit alternatives and to facilitate the selection of those with lowest costs. Simulations are used to compute expected net present values for retrofit alternatives. Penna et al. (2015) [30] develop a genetic algorithm and simulation model to investigate promising energy efficiency measures related to the building envelope and the thermal-conditioning system with respect to multiple competing objectives (Pareto approach). Their objectives are the economic performance, energy consumption, and thermal comfort of a building. However, the model does not consider retrofit measures with renewable energies. Asadi et al. (2011) [35] develop a multi-objective optimization model to select retrofit measures to minimize the energy use in a cost-effective manner, while satisfying several occupants' requirements. This model includes all technically feasible combinations concerning windows, insulation materials for the building envelope, and solar collectors, without being confined to a small set of predefined retrofit scenarios. It is implemented with a Tchebycheff programming simulation technique which is complex and difficult to extend. Rosso et al. (2020) [36] also implement a multi-objective optimization of building retrofits to minimize investment, energy demand or operational energy cost, and CO_2 emissions. To identify the optimal retrofit measures, they use a genetic algorithm with active archive and non-dominated sorting.

Antipova et al. (2014) [37] develop a fast mixed-integer linear program that identifies the alternatives with the lowest environmental impact. The program can be adapted to different climatic zones, but is limited to a few retrofit measures only. It considers different wall insulation materials, exchange of windows, and the installation of solar panels, while the replacement of the heating system or the installation of a ventilation system are missing. Jafari and Valentin (2017) [38] optimize the life-cycle cost for a specific building during its service life with respect to retrofit measures based on available equity. They use a simplified prediction method for the building's energy demand by integrating dynamic and static modeling and incorporating energy retrofitting decision-making uncertainties. However, only limited retrofit measures for a specific project are considered. Wu et al. (2015) [39] present a multi-objective optimization (trade-off) to minimize life cycle cost and greenhouse gas emissions via retrofits. Their approach consists of a dynamic energy demand simulation to depict a wide range of existing buildings. It is combined with a mixed-integer linear program.

The approaches by Wang et al. (2014) [32], Kumbaroğlu and Madlener (2012) [33], Ruparathna et al. (2017) [34], Antipova et al. (2014) [37], Jafari and Valentin (2017) [38], and Wu et al. (2016) [39] can be used or extended for German retrofitting projects. Moreover, they can be transferred to different building types and all of them include economic objective functions, among others. Only Kumbaroğlu and Madlener (2012) [33] quantify the CO_2 savings through the retrofit, whereby Wu et al. (2016) [39] quantify and maximize the savings of all greenhouse gases. Coupling effects[1] are only considered by Kumbaroğlu and Madlener (2012) [33]. Only Ruparathna et al. (2017) [34] and Jafari and Valentin (2017) [38] differentiate between equity and debt capital. No existing model is known to the authors that performs an economic optimization covering German buildings and German framework conditions of energy standards, retrofit costs, different financing alternatives and the funding systems of the BAFA, KfW, and German tax benefits. Thus, we develop an innovative optimization model for the economic assessment and selection of energy retrofits under German conditions. The model is capable of the following (requirements):

- Modeling German residential buildings, their building components, their retrofit status, and their energy performance

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[1] Coupling effect [40-41]: Energy retrofits are often planned when conventional retrofits are necessary anyway. The coupling effect has an impact on the cost planning of a retrofit, since often only additional energy-related costs of a retrofit measure are relevant then to a building owner. These costs can be considerably lower, if retrofit measures are coupled.

- Evaluating different retrofit measures and prices for the most common retrofit measures (insulation and retrofit of the building envelope components, exchange of the heating system with different technologies, installation of a ventilation system, auxiliary measures)
- Considering the coupling effect
- Integrating German tax advantages and public subsidies on federal level (KfW, BAFA) into the cost-benefit optimization
- Taking into account the technical standards, minimum requirements, and laws for energy retrofits in Germany
- Distinguishing different financing alternatives (with/without equity of different amounts)
- Allowing program implementation with a short computing time to allow multiple optimization runs for different scenarios

The output of the model provides information on financially optimal retrofit measures and their CO_2 impacts. In a case study, we apply the model to two representative buildings of the largest cohort of German SFHs from the 1960s and 1970s according to the European TABULA building typology [12].

2 Methods and Theory

The concept of the optimization model is developed as a mixed-integer problem (MIP/ pl. MIPs) in Section 2.1 and specified in a case study with data for two German buildings, German framework conditions, and exemplary retrofit scenarios in Section 2.2. The case study is implemented as a program in GAMS [42], a programming language that has the advantage of describing an optimization problem in a way that is very similar to its mathematical description. For solving MIPs, GAMS uses branch and bound algorithms. Appendix 1 contains detailed information on the database used in the case study. Appendix 3 contains our annotated code with all constraints in detail.

2.1. The Optimization Model

2.1.1 Target function and model structure

The target function TF describes the financial perspective of a self-using SFH owner. In the considered time period tp [a], owners wants to maximize the savings of energy costs after the retrofit (compared to before) sav [€], the financial benefits or tax advantages for the retrofit $benef$ [€] minus the investments for the retrofit measures inv [€] and the costs for a potentially necessary credit $cred$

[€]. All components of the target function depend on the vector variable mes [-], representing a bundle of selected retrofit measures. The amount of financial benefits depends on the vector variable $prog$ [-] representing a bundle of selected funding programs/ tax benefits. The target function describes the return on investment (ROI/ pl. ROIs) for an energy retrofit. The ROI is a main economic decision criterion that is suitable for planning energy retrofits [43].

The target function is formulated as:

$$max\ TF(mes) = \sum_{tp} sav(mes) + benef(mes, prog) - \left(inv(mes) + \sum_{tp} cred(mes, prog)\right)[€]$$

(Eq. 1)

To model the selected bundle of retrofit measures mes, the model uses an n-dimensional vector of binary variables of n individual retrofit measure (e.g. insulation of the walls, replacement of the heating with a heat pump). These equal 1 if a measure according to the optimization function is optimal and 0 if not. Similary, the vector $prog$ corresponds to an m-dimensional binary vector for retrofit funding programs, indicating whether a funding program is optimal for a maximized ROI. The constraints of this optimization model are calculations for the investment costs, financial benefits, and performance values (e.g. boiler efficiencies, heat distribution losses, wall insulation quality) depending on every possible combination of the n retrofit measures. With this information, it is possible to calculate the expected annual energy demand, costs, and CO_2 emissions prior to and after energy retrofits according to technical standards, described in Section 2.1.2 and Appendix 1. Furthermore, the model allows the inclusion of information on building parts that must be retrofitted/replaced anyway due to defects (coupling effect), which is often the initial motivation for building owners to plan comprehensive retrofits [40-41].

The outputs of the model are the maximized variables of the target function which are the optimal ROI TF, a bundle of optimal retrofit measures mes, financial savings sav, suggestions for the optimal funding programs/ tax benefits $prog$ and the amount of financial benefits $benef$, as well as investment and credit costs inv and $cred$. Additionally the output provides information on energy/ CO_2 performance values of the building after retrofit and the comparison to the building performance before retrofit. An overview of the model components is illustrated in Figure 1.

Target function

Maximizing the savings of energy costs and financial benefits (subsidies) minus the initial investments and credit costs of a retrofit within a certain planning time period

Model parameters

Input mask for model/ optimization parameters adaptable by the user	Calculation parameters	Characteristics of the considered SFHs
Includes: - Selecting a single family house - Selecting building components with retrofit necessities - Building specific conditions (available building infrastructure) - Owner specific conditions (considered planning time period, equity, annual taxes)	Includes: - Energy prices for energy sources - CO2-factors for energy sources - Primary energy factors for energy sources - Interest rate for private credits - Market dynamics (annual price changes for energy sources, annual change of CO2-factors of energy sources) - Technical standard parameters (energy efficiency of modern heat boilers, energy performing factors of modern heat pumps, shares of energy need covered by solar systems, districbution losses of heating pipes, heat recovery efficiency factors of ventialtion, auxiliary elictricity energy needs of the heating and ventialtion systems)	Includes: - Areas of building envelope components (roof, walls, floors, windows, door) - Quality parameters of building envelope components (U-values, g-values, assumption on the air tightness of the building envelope) - Quality parameters for the technical buidling system (energy source of the heating system, efficiency of the heating system, quality of the heating pipes, existstance of a solar system, existance of a modern ventialtion system with heat recovery, area-specific el. auxiliary energy need) - Other building characteristics (room height, shape of the roof)

Constraints (calculations for every possible combination of retrofit measure)

Investment for retrofit	Building performance after retrofit	Financial benefits
Takes into account: - Calculation of investments for the retrofit of building components depending on the retrofit quality (e.g. U-value of a wall insulation) - Considering full costs and additional energy-quality-related investment costs for every building component - Calculation of the sum of additional costs and the sum of full costs for the whole retrofit	Takes into account: - Annual need for delivered energy - Annual primary energy need - Annual CO2-emissions - Annual energy costs - Comaprision of performance before retrofit with performance after retrofit	Takes into account: - Credit benefits and investent benefits - Minimum standards for receiving funding (e.g. technical minimum requirements for retrofitted components) - Requirements for the combination of programs

Output variables

- Maximized target function with financial savings/ additional expenditure for the considered time period after retrofit
- Suggestions for optimal retrofit measures
- Suggestions for optimal financial benefit programs/ tax advantages
- Performance characteristics of the optimally retrofitted building (annual energy costs, annual CO2-emissions, annual energy needs)
- Comparision values to indicate performance differences before and after the optimal retrofit
- Amount of optimal retrofit invests (full costs and additional costs for every retrofitted building component)

Figure 1: Model components of the optimization model including model input parameters, calculation modules, and model outputs. Details for the implementation of this model for German buildings are introduced in the case study in Section 2.2. (Explanations [44]: U-value [W/(m^{2}K)]: coefficient for thermal transmittance through building components mainly between indoor and outdoor / g-value [-]: coefficient commonly used in Europe to measure the solar energy transmittance of windows. A g-value of 1 describes full transmittance, while a value of 0 describes zero transmittance)

2.1.2 Technical model to calculate the heating needs of an SFH

The basic structure to calculate the energy needs of a building within the model is based on the TABULA calculation method for energy use from heating and domestic hot water [45]. It applies the seasonal method according to the standard EN ISO 13790 [46] of the German institute for standardization (DIN). This standard specifies calculation methods for determining the annual energy requirement for space heating and cooling of a residential building, assuming a constant indoor temperature. The methods include the calculation of the heat transfer through the building envelope by transmission and ventilation. The heat balance of the building also includes the contribution of internal and solar heat. To achieve a fast computation time for the optimization model, we developed an MIP without non-linear equations by modifying the TABULA approach. The calculation equations (Eq. 2 – Eq. 13) and their modifications are listed in Table 1. The modifications particularly affect the calculations of the energy needs for heating and hot water, the non-renewable energy needs for the heating system, and the needs for delivered energy for heating and ventilation (in Eq. 6, Eq. 8 and Eq. 10). For these modifications, we used simplified, linear factors and standard values of DIN 4108-6 [47] for annual period accounting, with a heating period of 185 days for an averaged climate[2] as well as standard values of DIN 4701-10 [48]. Moreover, to linearize all equations we used fixed efficiency parameters, loss parameters, and specific energy needs.[3] Figure 2 schematically illustrates the implemented calculation of the thermal energy balance of a building and the subsequent primary energy needs of the building's heating system in the optimization problem. The model focuses on retrofit measures on the building envelope and fixed installed technical equipment; the exchange of appliances like more efficient appliances (e.g. efficient dishwashers, shower heads, fridges) are not considered. The calculation procedure and references are explained in detail in Appendix 1 in the context of to the case study described in Section 2.2.

Table 1: New simplified calculation method for the building performance for energy, CO_2 emissions, and energy costs [45-48]

Parameter	Equation	Notation
Heat transfer coefficient by transmission H_{tr} (Eq. 2) (TABULA, 2013)	$H_{tr} = \sum_{envelope\ part\ i} b_i * U_i * A_i + thf * A_{env} \left[\frac{W}{K}\right]$	b: Standard soil adjustment factor [-] U: U-value [W/m²K] A: Size of an area [m²] thf: Standard thermal bridging surcharge factor [W/m²K] A_{env} : Area of the building envelope [m²]
Heat transfer coefficient by ventilation H_{ve} (Eq. 3) (TABULA, 2013)	$H_{ve} = c_{p_{air}} * (n_{air_{use}} + n_{air_{\inf}}) * A_{ref} * h_{room} \left[\frac{W}{K}\right]$	$c_{p_{air}}$: Volume-specific heat capacity of air [Wh/m³K] $n_{air_{use}}$: Air change rate by use [1/h] $n_{air_{\inf}}$: Air change rate by infiltration [1/h], A_{ref}: Reference area of the building

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[2] For our program, we used climate values for Germany according to our case study.

[3] For our program, we used values that rely on estimators on technical standards deduced from market investigation of currently available building components in Germany according to our case study.

		[m²] h_{room}: Height of the buildings' rooms [m]
Solar heat load during heating season Q_{sol} (Eq. 4) (TABULA, 2013)	$Q_{sol} = g_{window} * F_{sh} * (1 - F_F) * F_W * \sum_{cardinal\ direction\ i} A_{window_i} * I_{sol_i} \left[\frac{kwh}{a}\right]$	g_{window}: g-value of the windows [-] F_{sh}: External shading [-] F_F: Frame area fraction [-] F_W: Non-perpendicular [-] A_{window}: Area size of windows [m²] I_{sol}: Solar global radiation [kWh/m²a]
Internal heat gain Q_{int} (Eq. 5) (TABULA, 2013)	$Q_{int} = f_u * d_{hs} * \varphi_{int} * A_{ref} \left[\frac{kwh}{a}\right]$	f_u: Conversion factor for converting days into hours [kh/d] d_{hs}: Length of the heating season [d/a] φ_{int}: Average thermal output of internal heat sources [W/m²] A_{ref}: Reference area of the building [m²]
Energy need for heating Q_H (Eq. 6) (DIN 4108-6 modified)	$Q_H = c_{dd} * (H_{tr} + \eta_{ve} H_{ve}) - c_{he} * (Q_{sol} + Q_{int}) \left[\frac{kwh}{a}\right]$	c_{dd}: Factor considering the temperature difference between inside and outside [kKh/a] c_{he}: Utilization rate of heat gains [-] η_{ve}: Efficiency factor of the ventilation system [-]
Energy need for hot water Q_W (Eq. 7) (DIN V 4701-10)	$Q_W = q_W * A_{ref} \left[\frac{kwh}{a}\right]$	q_W: Energy need for hot water [kwh/m²a] A_{ref}: Reference area of the building [m²]
Non-renewable energy need for the heating system Q_E (Eq. 8) (DIN V 4701-10 modified)	$Q_E = \frac{\left(\frac{\eta_{s_H}}{\eta_p} * Q_H + \eta_{s_W} * Q_W\right)}{\eta_h} \left[\frac{kwh}{a}\right]$	η_{s_H}: Factor for a possible reduction of the heating energy need by the use of a solar thermal system [-] η_{s_W}: Factor for a possible reduction of the energy need of hot water by the use of a solar thermal system [-] η_h: Efficiency rate of the heating generation system [-] (For heat pump: Annual performance factor, for boilers and district heat: Annual efficiency rate) η_p: Factor for the thermal quality of the heating pipes in the building [-]
Auxiliary electrical energy need for the heating and ventilation system Q_{aux} (Eq. 9) (TABULA, 2013)	$Q_{aux} = aux_{el} * A_{ref} \left[\frac{kwh}{a}\right]$	aux_{el}: Factor for the auxiliary energy need of the heating system and the ventilation system [kWh/m²a]

Need for delivered energy for heating and ventilation Q_{del} (Eq. 10) (TABULA, 2013 modified)	$Q_{del} = Q_E + Q_{aux} \left[\frac{kwh}{a}\right]$	
Total primary energy need for the heating system PE (Eq. 11) (TABULA, 2013)	$PE = Q_E * f_{PE} + Q_{aux} * f_{PE\,el} \left[\frac{kwh}{a}\right]$	f_{PE}: Primary energy factor of the used energy source [-]
Total CO₂ emissions of the heating system CO_2 (Eq. 12) (TABULA, 2013)	$CO_2 = Q_E * f_{CO_2} + Q_{aux} * f_{CO_2\,el} \left[\frac{g}{a}\right]$	f_{CO_2}: CO₂ factor of the used energy source [g/kWh]
Total energy costs of the heating system C (Eq. 13) (TABULA, 2013)	$C = Q_E * p + Q_{aux} * p_{el} \left[\frac{€}{a}\right]$	p: Energy price of the used energy source [€/kWh]

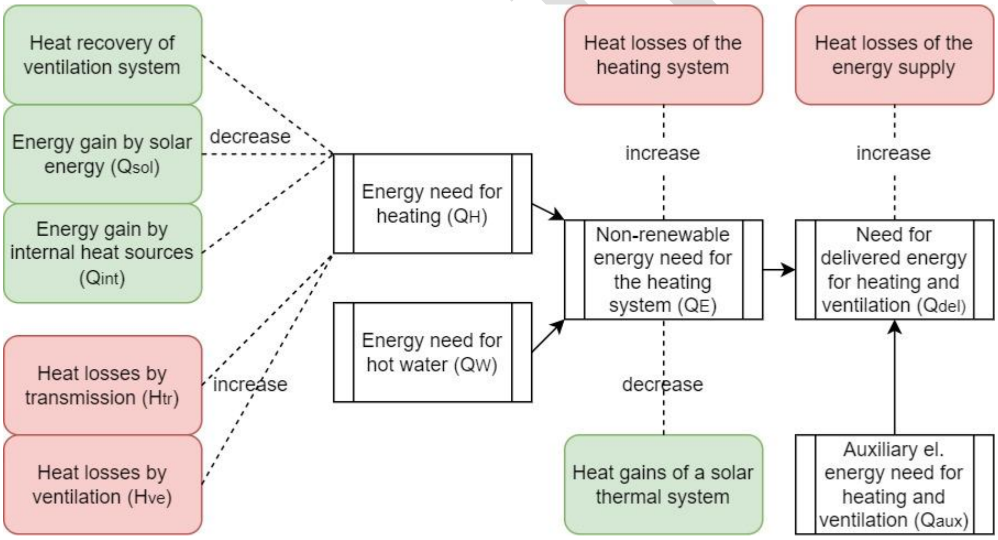

Figure 2: Overview of the energy losses and energy gains of a building (own illustration)

2.2 Case Study for German Buildings from the 1960s and 1970s

2.2.1 Considered buildings

Two German SFHs are examined that are representative of SFHs construction for the decades 1958-1968 and 1969-1978. Both buildings are modeled with their average energy quality in 2017. In terms of quantity and energy needs, both SFHs are representative of the important German building category of SFHs from the 1960s and 1970s with respect to the CO_2 reduction potential (Section 1). The underlying data for the buildings' modelings are based on the TABULA building typology, which provides a comprehensive and validated database [49]. A brief description of the buildings is shown in Table 2. Their detailed technical building data is listed in Appendix 1 (Table A1.1.). For our optimization program, we further assume that the considered buildings can be connected to a district heating system, that gas heating infrastructure is locally available, that the property's soil allows deep drilling and is large enough to install ground collectors and ground probes for heat pumps, and that there is enough space for the installation of a solar system on the building's property.

Table 2: Basic characteristics of the considered German SFHs of the construction decades 1958-1968 and 1969-1978 [49]

Characteristics	SFH_E 	SFH_F 
Number of existing buildings in Germany	1.509 million	1.507 million
Year of construction	1958-1968	1969-1978
Reference floor area	121.2 m²	173.2 m²
Area of the building envelope	463.8 m²	549.2 m²

2.2.2 Financial benefits and tax advantages for energy-related retrofits

In the case study, we include financial benefits from the KfW bank and the BAFA as well as tax benefits (status: 03/2020). An overview of the funding programs, their allowed combinations, and minimum standards are summarized in Table 3. In general, combining two funding instruments for a single measure is not possible, while a combination of grants and credits is allowed. Some funding instruments are only applicable in combination with other instruments. We only consider support programs for retrofit measures and funding conditions relevant to the focus of this study. We do not consider retrofit measures that do not affect a building's thermal energy needs such as retrofitting of electric or water distribution systems. For more details, we refer to the explanations of the funding programs and their funding guidelines [19,24,26].

Table 3: Overview of German subsidy instruments for the thermal energy-efficient retrofit of owner-occupied SFHs [19,24,26] (Explanations: KfW standard [19]: KfW standards were defined by the KfW bank and indicate the thermal quality of a building according to its annual primary energy requirement and transmission heat loss. CO_2 emissions are not relevant. The lower the standard, the lower the primary energy requirement of a building.)

Name	Object of the program	Allowed combinations with other programs	Maximum credit per building and interest rate	Direct financial benefit per building	Financially supported measures and funding conditions
KfW 151/ 152	- Retrofit with high efficiency KfW standard - Single energy efficiency measures	Possible with: KfW 167, KfW 431	- Up to 120,000 €/ SFH for efficiency standard of at least KfW 115 for max. 30 years - max. 50,000 €/ SFH for single measures for max. 30 years 0.75% per year (fix for 10 years)	- KfW 55: 40% of retrofit costs, max. 48,000 €/ SFH - KfW 70: 35% of retrofit costs, max. 42,000 €/ SFH - KfW 85: 30% of retrofit costs, max. 36,000 €/ SFH - KfW 100: 27.5% of retrofit costs, max. 33,000 €/ SFH - KfW 115: 25% of retrofit costs, max. 30,000 €/ SFH - Single measures: 20% of retrofit costs, max. 10,000 €/ SFH	- Insulation of walls: Max. allowed U-value [W/m²K]: 0.2 - Insulation of roofs: Max. allowed U-value [W/m²K]: 0.14 - Insulation of floor ceilings: Max. allowed U-value [W/m²K]: 0.25 - Renewal of windows: Max. allowed U-value [W/m²K]: 0.95 - Renewal of doors: Max. allowed U-value [W/m²K]: 1.3 - Installation/ renewal of energy-efficient ventilation systems - Renewal of heating systems: Connection to district heating network and heat exchanger, pellet boilers, gas condensing boiler, heat pumps, solar systems (a single measure financial support for a heating system with only renewable energies is not possible. For this it needs the BAFA program as described below.) - Insulation of heating pipes
KfW 167	- Heating systems with renewable energies	Possible with: KfW 151/152, KfW 430, KfW 431, BAFA program for heating with renew. Energies	- Up to 50,000 €/ SFH for max. 10 years 1% per year	-	Same as BAFA program for heating with renew. energies
KfW 430	See KfW programs 151/152	See KfW program 151/152	-	See KfW program 151/152	Same as KfW 151/152
BAFA heating with renew. energies	- Heating systems with renew. Energies	- Possible with: KfW 167, KfW 431	-	- Solar systems (without retrofit of the heating system): 30% of retrofit costs - Hybrid heating system (combination of solar and pellet), pellet boilers and heat pumps: 35% of retrofit costs/ SFH (45% if existing system works with oil) - max. 50,000 €/ SFH	- Pellet boiler: Minimum efficiency factor: 89% - Heat pumps: Minimum annual performing factor for air [-]: 3.5, Minimum annual performing factor for ground heat [-]: 3.8 - Insulation of heating pipes in combination with the retrofit of the heating system with Solar systems, heat pumps and pellet boilers
Tax bene-fits 2020	- All kinds of energy efficiency measures - Alternative to all the programs of KfW and BAFA described in this table	-	-	- 20% of retrofit costs, max. 40,000 €/ SFH tax deductible within 3 years The collective income tax, reduced by the other tax reductions: 1. Year: Tax reduced by 7% of the retrofit costs, max. 14,000 €/ SFH, 2. Year: Tax reduced by 6% of the retrofit costs, max. 12,000 €/ SFH, 3. Year: Tax reduced by 6% of the retrofit costs, max. 12,000 €/ SFH	Same as all measures and conditions of KfW 151/152 + BAFA program for heating with renew. Energies + KfW 431

2.2.3 Retrofit measures and standards

The retrofit measures included in the case study that can be freely combined with each other are:

- Façade:
    - New windows (2 panes/3 panes),
    - new door,
    - insulation of the walls (U-value between 0.1-0.24 W/m²K),
    - insulation of the roof (U-value between 0.1-0.3 W/m²K),
    - insulation of the floor (U-value between 0.1-0.3 W/m²K)
- Heating system:
    - Replacement of the heating system with a heat pump (with a ground probe/ with a ground collector/ for outside air) both for heating and hot water,
    - with a fossil fuel-based district heating system,
    - with a boiler (gas condensing boiler/ oil condensing boiler/ pellet boiler),
    - with an optional solar system (for hot water only or for the full heating system) suitable for the building
- Others:
    - Renewal of heating pipes,
    - installation of a central ventilation system with heat recovery

In Germany, the technical requirements for thermal energy retrofits are regulated in the German Building Energy Act (Gebäudeenergiegesetz (GEG)) [50], which relies on the previous Energy Saving Ordinance (Energieeinsparverordnung (EnEV)) [51]. It defines retrofit obligations of energy-related components of buildings as well as their minimum energy standards. In our program, the quality parameters for retrofitted building components are estimated average values according to standards of currently available building components in Germany. All energy values used comply with the GEG 2020. The detailed measures, standards, and minimum requirements of our program are listed in the database in Appendix 1 (Table A1.2.). For further information on the qualitative scope of the retrofit measures that are not important for the thermal modeling (e.g. average sizes and standard construction material of retrofit measures) we refer to the studies by Hinz [40,41], which are introduced in the following section.

2.2.4 Retrofit costs

The cost functions for the energy retrofit of building components for the case study relate to the component surfaces and the building reference area, and are based on Hinz (2015) [41]. The database relies on a very comprehensive and high-quality study about German energy retrofits evaluating retrofit projects of 1,200 residential buildings, of which approx. 780 are single and two-family houses. The costs for heat pumps also rely on Hinz (2012) [40]. We adjusted these values to the first quarter of 2020 by using the same construction price index for the maintenance of residential buildings including the value added tax of Destatis [52], as in Hinz et al. (2012) [40], and multiply all costs by a factor of 1.182. More recent retrofit cost data was not available for all considered retrofit measures. In our model, we differentiate between full retrofit costs and additional retrofit costs. This difference takes into account the coupling principle. The full retrofit costs describe the whole energy-related and energy-unrelated investments. The additional costs only quantify the additional costs for a higher energy quality than the current minimum standard. All modeled cost functions are listed in Appendix 1 (Table A1.2.).

2.2.5 Scenario definition

We define 48 different scenarios (4x3x4 alternatives) for each building: First, we consider four planning periods of 5, 10, 15, and 20 years that lie within the range of usual economic planning. Second, we consider building owners with no (0€), medium (25.000€), and high equity (100.000€) available for the retrofit investment; if higher investments are optimal the model calculates respective credits by a private bank or funding programs as described in Section 2.2.6. Third, we consider four different packages (P1-P4) of necessary retrofit measures to take into account the coupling effect. These necessary retrofits cover defect/old building components that have to be retrofitted anyway. In addition to the necessary retrofit measures, which are specified in the individual retrofit packages, any other additional retrofit measures described in Section 2.2.3 can be selected within the framework of the optimization. The packages cover common retrofit necessities for SFHs. They also cover different parts of the building and different extents of retrofit efforts.

These are:

- (P1) No retrofit necessary,
- (P2) Retrofit of the building envelope necessary (including the insulation of walls and roof, and the exchange of windows and the door),

- (P3) Retrofit of the heating system necessary (including the exchange of the heat generator and the insulation of heating pipes), and
- (P4) Full retrofit necessary (including the envelope as described in (P2), the insulation of floors, the replacement of the heating system as described in (P3), and the installation of a new ventilation system).

2.2.6 Further data and assumptions

The data used on prices for energy sources and price changes for the considered planning periods, primary energy factors, CO_2 factors, and factor changes for the considered planning period are summarized in Table 4 and in more detail in Appendix 1 (Table A1.3.). For credits that do not belong to the funding instruments but are offered by a private bank we calculate with an interest rate of 1.2%, which corresponds to the effective annual construction interest rate of the common credit institutions in Germany (e.g. local credit institutes such as Sparkasse and Volksbank [e.g. 53-55]). The costs for a credit follow the nominal credit costs and we assume that the credit is paid back within the considered time period. For state credits from KfW funding programs that expire after 10 years, we assume constant interest rates for the planning periods of 15 and 20 years. We do not consider opportunity profits if the equity is used for investments other than a retrofit. We assume that the annual tax obligations of a retrofitter are higher than the possible tax benefits of a retrofit.

Table 4: Boundary conditions for the case study (primary energy factors and CO_2 factors [56], [57]; CO_2 factor growth rates [58]; prices [59-60]; price growth rates [61])

Energy source	Oil	Gas	District heat	Pellets	Electric energy
Primary energy factors [-]	1.1	1.1	1.3	0.2	1.8
CO_2 factors [-]	310	240	280	40	550
Rates of annual CO_2 factor growth [-]	1	1	1	1	0.966
Prices [€/kWh]	0.0413	0.0661	0.0907	0.0477	0.3071
Rates of annual price growth [-]	1.05	1.011	1.005	1	0.997

3 Results

Both case study buildings show very similar results and patterns across the evaluated retrofit scenarios. There are minor differences regarding optimal retrofit measures, optimal financial benefit programs, and quantitative results. Detailed optimization results are listed in Appendix A2.

3.1 Optimization results for SFH_E and SFH_F

3.1.1 Selected retrofit measures

For both building types, the installation of a pellet heating system with a solar system for hot water was selected as optimal in all optimization scenarios except for package P1 (no retrofit necessity) over a planning period of 5 years. For packages P1 and P3, no additional measures for the building envelope are recommended. For retrofit packages P2 and P4, with comprehensive retrofit necessities of the building envelope, insulation of the roof, walls, and floor for both buildings with the highest U-value of 0.1 W/m²K is optimal. For all scenarios where windows are renewed, 2-pane windows are optimal. Only for a planning time of 20 years, the use of 3-pane windows is preferred to 2-pane windows for both building types.

3.1.2 Selected benefit programs

For all considered optimization scenarios, the use of tax benefit programs and private credits plays no role. Instead, the program 430 and the programs 151/152 respectively are optimal for all optimization scenarios with comprehensive retrofits of the building envelope (packages P2 and P4). For packages P1 and P3, where only a renewal of the heating system is recommended, the program of BAFA (combined with the KfW 167 program in the scenarios with required credits) is optimal.

3.1.3 Target function/ return on investment

Overall, almost all optimal calculated energy retrofits lead to large savings, offsetting the retrofit investments within 20 years. Even extensive retrofits can be attractive from an economical point of view (Figure 3). For SFH_E with full equity financing and optimal measures, all retrofit packages lead to a positive ROI within 20 years. Only for SFH_F, no positive target function can be found with a full retrofit (P4) within 20 years.

The financial cost-benefit ratio for measures on the heating system is comparably better than for measures on the building envelope. While retrofits without retrofit necessity (P1) or with a necessary retrofit of the heating system have a positive ROI after 10 years already, the retrofit packages with extensive retrofits of the building envelope (P2, P4) have a positive ROI only after a longer period of time. For all scenarios, it is clear that credit costs are negligible compared to the total costs; they are less than 3% of the investments in all scenarios, even for planning times of 20 years. We can see that with current interest rates, the available retrofit equity has a small impact on the total ROI value. To better illustrate the results in the following result sections, we work with average values (average ROI with differing funding periods between 5 and 20 years) for the retrofit scenarios with different amounts of equity (Figure 4, Figure 5, Figure 6).

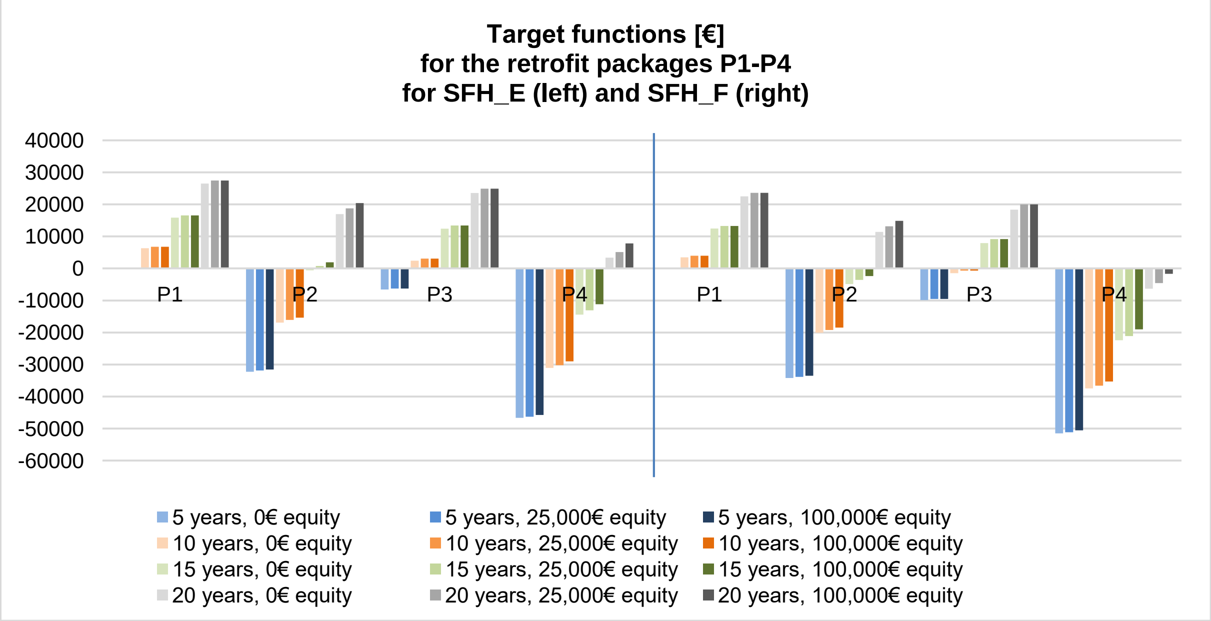

Figure 3: Target function value (return on investment) of the optimization scenarios for different retrofit packages (P1-P4) and different equities, aggregated with respect to financing periods (between 5 and 20 years)

3.1.4 Investment and financial benefits:

The optimal investments for the retrofits of the two buildings reach about 104,000 € for the SFH_E and up to about 110,000 € for the SFH_F in the scenarios with necessity for full retrofit (Figure 4). As expected, in the scenarios with no or just a few retrofit necessities (P1, P3) investments are lower. The financial benefits of KfW, BAFA and tax benefits reach up to about 41,500 € for SFH_E and up to about 44,000 € for SFH_F for the full retrofit scenarios (P4) (Figure 4). All optimal retrofit measures and funding programs recommended by the program are broken down for all scenarios in Appendix A2.1.

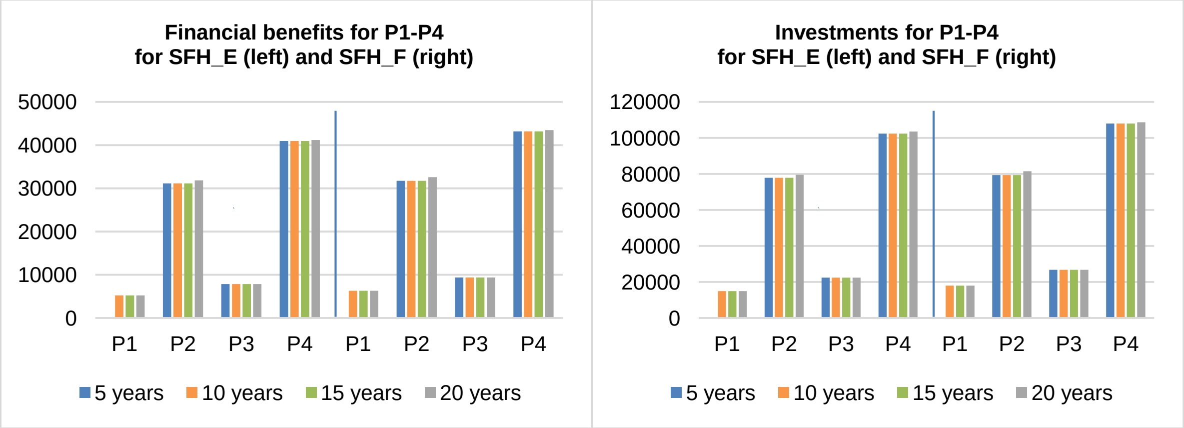

Figure 4: Investments and financial benefits (of KfW, BAFA, and tax benefits) for optimal retrofits (average values for scenarios with different amounts of equity between 0 €, 25,000 €, and 100,000 €)

Figure 5 shows that the energy-related additional costs for a higher/optimal energy standard after retrofit are only a small share (27-36%) of the full costs when conventional retrofits are necessary anyway (P2-P4).

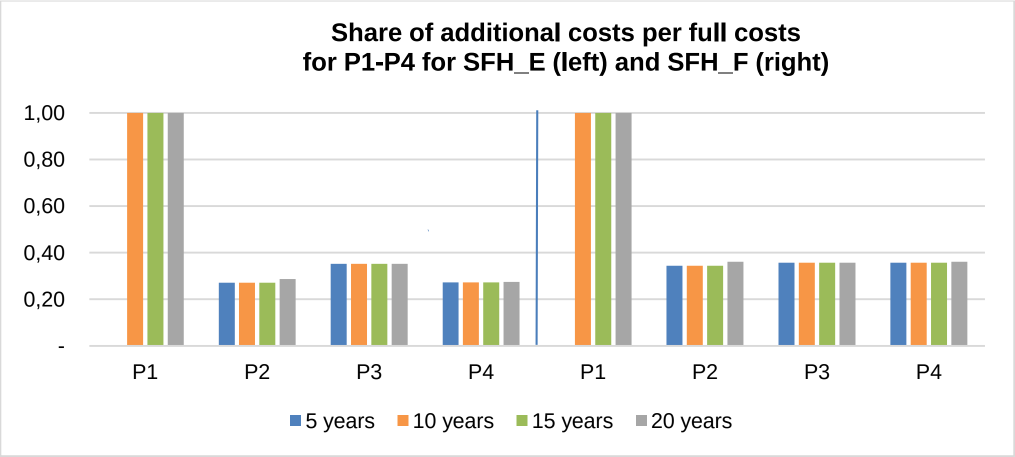

Figure 5: Shares of additional energy-related costs per full costs of conventional retrofits for economically optimal retrofits (average for scenarios with different amounts of equity between 0 €, 25,000 €, and 100,000 €)

3.1.5 Performance indicators:

The performance indicators in the optimization are the annual savings in energy (delivered and primary energy), annual CO_2 emissions, annual energy costs (heating) and the KfW standard. The performance values of the buildings in the initial state before retrofits calculated by the program are shown in Table 5.

Table 5: Characteristic values for SFH_E and SFH_F for the initial state without retrofit measures

	SFH_E	SFH_F
Annual delivered energy need [kWh]	52,385	49,768
Annual primary energy need [kWh]	58,175	55,533
Annual energy costs [€]	3,653	3,561
Annual CO_2 emissions [kg]	12,817	12,293
KfW standard	613	515

The performance after an optimal retrofit according to the model is shown in Figure 6 as the proportion of the original energy demand.

For all scenarios with recommended measures, considerable CO_2 savings can be achieved, with the optimal solution having only 7-18% of the original annual emissions. Large savings in delivered energy can only be achieved if the building envelope is retrofitted (P2, P4). Here, the savings of delivered energy are up to 90%. In the scenarios with heating system retrofits only, the possible delivered energy savings are comparably small. The savings of primary energy need are up to 95%. Correspondingly, the reduction in energy costs is significant for all scenarios where retrofit measures are recommended. The reduction in operational costs is greatest when measures lead to a reduction of the energy need (in the scenarios with a retrofitted envelope). For all scenarios with recommended measures, the new operational costs are between 15% and 62% of the initial value.

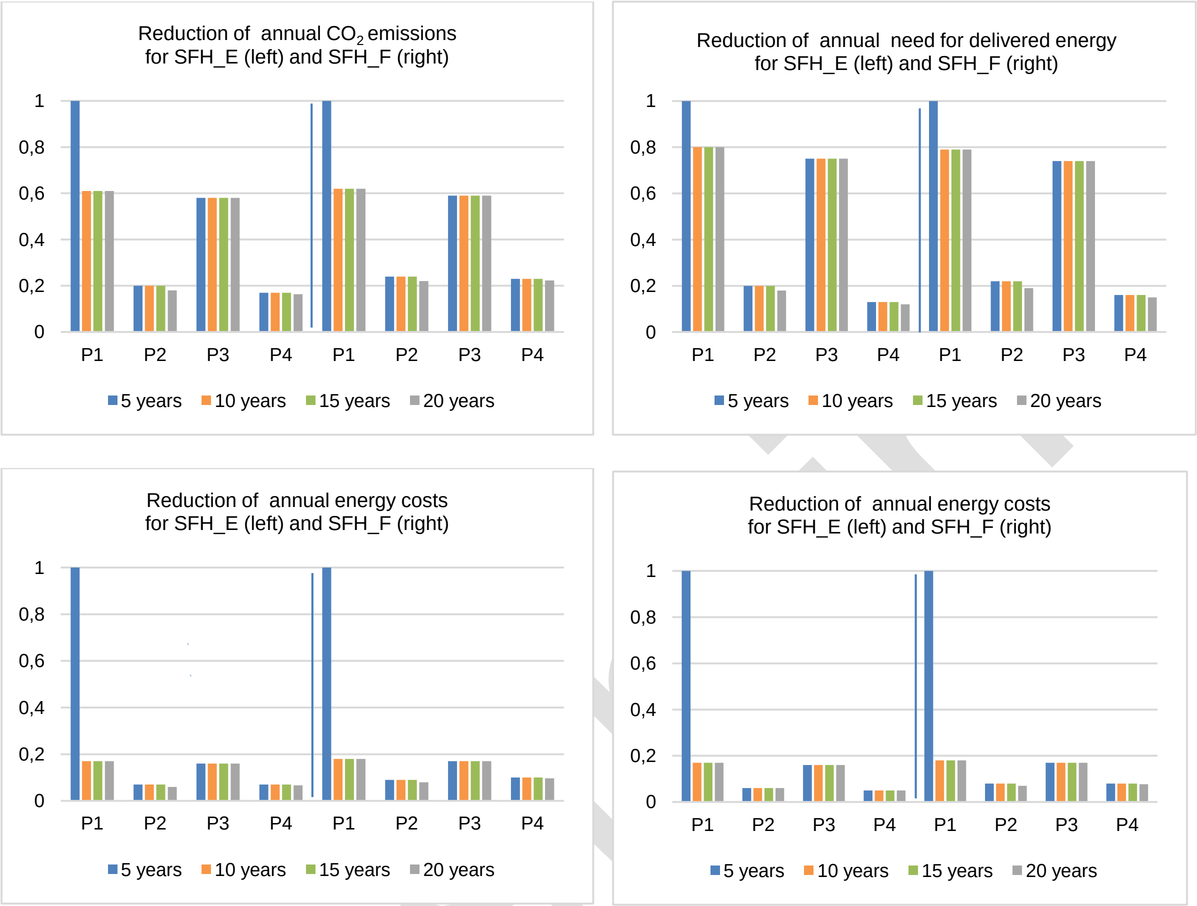

Figure 6: Annual reductions of CO_2 emissions, delivered energy need, primary energy need, and energy costs for the reference year 2020 (average for scenarios with different amounts of equity between 0€, 25,000 €, and 100,000€)

3.2 Result analysis

The case study shows that most economic retrofits of SFHs from the 1960s and 1970 can lead to considerable CO_2 savings, even within a short period of 5-10 years. A reduction in annual CO_2 emissions down to 7-18% of the of pre-retrofit emissions was found for all scenarios for a 10-year planning period, and for a 5-year planning period with retrofit necessities. Within 20 years, all energy retrofits of the two SFH representatives are amortized or almost amortized through energy savings, even in a scenario with a full retrofit necessity. Under the given framework conditions, retrofit measures that exceed the regulated minimum energy standard of building components prove to be optimal in almost all scenarios (see bold retrofit measures listed in Table A2.1). In the scenarios with retrofit necessities, the financial funding compensates for the additional energy costs of the retrofit measures in almost all cases. This is not the case for scenarios without retrofit necessity (P1) where the energy-related additional costs are equivalent to the full costs.

The conditions of German funding programs are not designed to maximize the CO_2 savings of an energy retrofit. There are considerable differences in the funding efficiencies for saved emissions per euro of financial benefit for the individual scenarios (Figure 7). The funding invested to reduce an annual ton of CO_2 ranges from 493 € (in P1) to 3,747 € (in P4). While the replacement of the heating system in our study leads to high CO_2 savings, additional measures on the building envelope (P2, P4) only lead to relatively small reductions, but are highly subsidized.

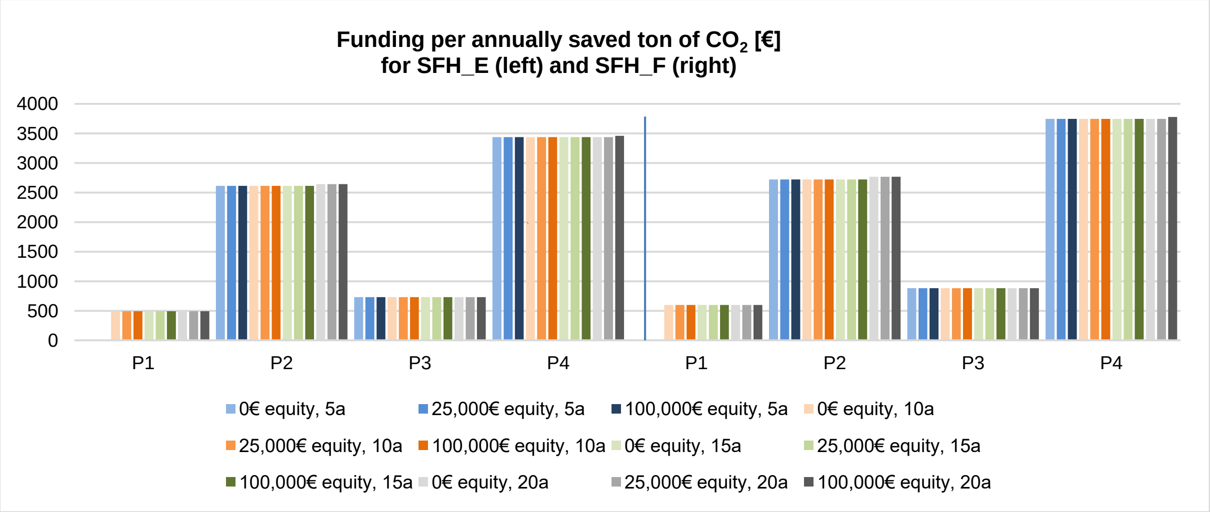

Figure 7: Amount of funding [€] per annually saved ton of CO_2 emissions (average for scenarios with different amounts of equity (0 €, 25,000 € and 100,000 €) and investment periods (5, 10, 15 and 20a)

3.3 Model validation and program computing time

To validate the technical model, with its simplified assumptions for the calculation of the energy needs of the considered buildings, we compared it with calculations and empirical values from TABULA [49]. For both considered SFHs, TABULA provides data for three different energy performance levels (V1, V2, V3) achieved by different retrofit alternatives, which we tested with our model. A performance comparison (Table 6, Figure 8) shows that our simplified procedure provides structurally comparable values like those given by the TABULA Web tool [49], whose calculation approach is based on German DIN standard calculations, for the two considered SFHs. However, the theoretical calculations deviate from empirically averaged recorded values for these three energy performance levels. User behavior plays a major role, particularly in the case of low energy performance buildings, where users tend toward energy-saving behavior, for example by reducing average room temperature or by not heating unused building areas [45]. This is indicated by “the broad spread of consumption values which can be observed in thermally similar buildings and which is the result of different thermal comfort levels” [45].

For the three given energy performance levels and two building types, the most significant differences for the calculated and empirical energy needs occur for energetically poorly performing buildings (V1) (Table 6). The average inaccuracy between TABULA calculations and empirical values is 24%. With 27%, our new linearized method is only about 3% worse than the TABULA calculation method. However, our program has the advantage of a low complexity and a very fast computing time (0.5-3.5 seconds in all 96 case study scenarios) compared to non-linear problems (hours to days).

Table 6: Need for delivered energy calculated with our simplified approach compared to calculated and measured values according to TABULA [49]

Building	SFH_E				SFH_F			
	Technical standard (U-values [W/m²K])	New simplified approach	TABULA calculated	TABULA empiric data	Technical standard (U-values [W/m²K])	Simplified Approach	TABULA calculated	TABULA measured
V1: Annual delivered energy without retrofit	Roof (0.8), Wall 1 (1.2), Wall 2 (0.8), Floor (1.08), Windows (2.8), Door (3) Old gas boiler from 1987-1994	432.22 kwh/m² (179%)	407.3 kwh/m² (169%)	241.4 kwh/m² (100%)	Roof (0.5), Wall 1 (1), Floor 1 (0.77), Floor 2 (1), Windows (2.8), Door (3) Old gas boiler from 1987-1994	287.35 kwh/m² (133%)	313.9 kwh/m² (146%)	215.4 kwh/m² (100%)
V2: Annual delivered energy with good quality retrofit	Roof (0.41), Wall 1 (0.23), Wall 2 (0.21), Floor (0.31), Windows (1.3), Door (1.3) Gas boiler from 1995	155.53 kwh/m² (102%)	173.1 kwh/m² (113%)	152.8 kwh/m² (100%)	Roof (0.18), Wall 1 (0.22), Floor 1 (0.28), Floor 2 (0.3), Windows (1.3), Door (1.3) Gas boiler from 1995	96.64 kwh/m² (77%)	132.4 kwh/m² (105%)	125.5 kwh/m² (100%)
V3: Annual delivered energy with very high quality retrofit	Roof (0.14), Wall 1 (0.13), Wall 2 (0.12), Floor (0.23), Windows (0.8), Door (0.8) Gas condensing boiler with high efficiency, ventilation system with 80% heat recovery, solar system for hot water covering 60% of heat production	69.23 kwh/m² (112%)	59.6 kwh/m² (96%)	62.0 kwh/m² (100%)	Roof (0.09), Wall 1 (0.13), Floor 1 (0.21), Floor 2 (0.23), Windows (0.8), Door (0.8) Gas condensing boiler with high efficiency, ventilation system with 80% heat recovery, solar system for hot water covering 60% of heat production	55.35 kwh/m² (112%)	46.8 kwh/m² (95%)	49.3 kwh/m² (100%)

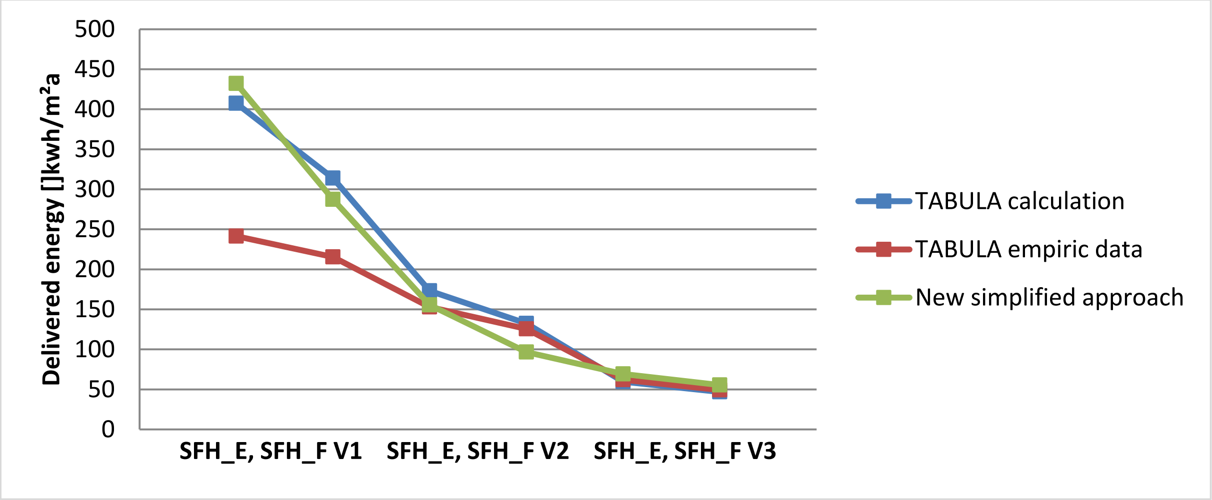

Figure 8: Comparison of the new simplified approach for the calculated and measured (empiric) delivered energy need according to TABULA [49] for different retrofit qualities V1, V2, and V3 and the two considered SFHs

3.4 Sensitivity analysis

There are several parameters in the model implemented in our case study program that could be considered for a sensitivity analysis which are neither covered by scenarios of our case study nor are fixed building parameters. These are: energy prices, energy factors and CO_2 factors, changes in prices and factors within the planning time, and technical parameters. As the energy prices are part of the target function and highly relevant to calculate the return on investment, we selected them for our sensitivity analysis. We increased and decreased the energy prices by 10% (90 and 110% of the standard price level) in all scenarios.

Our analysis found that with these price changes, the program results remain structurally the same (Figure 9). Only individual optimal retrofit measures are slightly different within a scenario (e.g. recommendation of 3-pane windows instead of 2-pane windows). For scenarios with a longer time period, changes of the target function are higher. This is to be expected, as higher/lower savings over a longer time due to changed energy prices compound over time. The target functions are on average significantly below / above 10% if the prices are adjusted by the same percentage, showing a relatively high sensitivity of the model to energy prices. With an increase in energy prices by 10%, the average target function is 26% above the average target function value at normal energy prices. With a decrease in prices by -10%, it is at 26% below average. However, we want to point out that with values around zero, even small absolute changes lead to large percentage deviations.

The detailed results of the sensitivity analysis for all scenarios are shown in Appendix 2.

Figure 9: Optimization results for different energy price levels (110% of prices and 90% of prices) – average target functions for the retrofit scenarios for the four retrofit packages

4 Discussion

The developed model complements existing models by introducing a simple approach to approximate the energy demand of residential buildings with a fast computing time. It is able to model energy retrofits for German buildings within German framework conditions, and provides decision support for the most economic retrofit measures for buildings from the perspective of self-using SFH owners. The case study shows that energy retrofits for the two analyzed German SFHs are financially attractive, having short time spans of 10-20 years for positive return on investments, even in scenarios with comprehensive retrofit necessities of the buildings. Since these two buildings are representative for SFHs for the 1960s and 1970s, comparable results can be assumed for many other buildings of this age group.

Looking at the energy and CO_2 savings of retrofits in our case study, we see that for heating system retrofits, energy savings are comparably small but they lead to higher operational CO_2 and cost saving than retrofit measures on the building envelope. Large energy savings of up to 90% can only be achieved by retrofit of the building envelope. Our study shows that the conditions of German funding programs are not designed to maximize CO_2 savings per funded euro. The funding invested to reduce an annual ton of CO_2 ranges from 493 € to up to 3,747 €. When prioritizing CO_2 savings for climate protection strategies, it might make sense to adjust the German funding conditions of BAFA, KfW and tax advantages to focus more on CO_2 emissions.

When looking at financial criteria for retrofit planning, it becomes clear that the amount of available equity for retrofits investments plays a minor role of less than 3% of the investment sum. Tax incentives do not appear financially attractive for retrofit measures that lead to the achievement of a defined KfW energy quality standard, or for the replacement of the heating system with a renewable energy-based system. In our case studies, the funding programs by the KfW and BAFA offer better funding options as selected by the optimization model. Comparing the results of our case study for the new funding conditions for energy retrofits of SFHs in Germany since 2020, we state a much better profitability than Runst (2016) [25], who found that retrofit measures are in general not profitable for building owners despite previous KfW and BAFA funding conditions.

We also want to highlight the shortcomings and possible improvements of our developed model. The model only includes retrofit measures on the building envelope or fixed installations/equipment relevant to the thermal energy demand of SFHs. Furthermore, the embodied energy and embodied emissions of the retrofit measures are also excluded. As described in Section 3.3., financial, energy, and CO_2 savings are systematically overestimated, in particular for buildings with low energy quality. This is a problem that affects all calculation approaches that do not take into account data for user behavior. For buildings with a low energy performance level, it appears that calculated energy needs are higher than empirically measured energy needs. To include the impact of user behavior, respective correction factors could potentially improve modeling results. Here, we decided not to include such factors, as German DIN standards and German funding conditions are based on theoretically calculated needs for standardized behaviour. Furthermore, there are also no generalizable correction factors that can be applied linearly and that are scientifically well-founded. TABULA (2017) currently only provides correction factors for exemplary buildings and exemplary retrofit measures [49].

For the cost calculation of retrofit measures as of 2020, we mainly used a database from 2015 from a comprehensive study. Since no current database of comparable quality and information is available, we used an adjustment factor for the cost of retrofit measures from the Federal Statistical Office. This does not take into account potentially differing price increases for different measures. The data could be updated with newer and more precise values.

In our model we do not consider the increased building values (asset) through investments. This leads to a systematic underestimation of the financial benefits of energy retrofits. Also, we neglected stochastic elements e.g. of costs due to possible defects of building technology or increasing maintenance costs for building technology with increasing age. As these effects are difficult to quantify, we decided to exclude these aspects.

Furthermore, the annual thermal building energy need was calculated via a simplification (linearization). This differs from current standard approaches and from the real energy consumption (Section 3.3). To improve our model, a higher modeling complexity working with energy demands instead of energy needs could be beneficial, e.g. based on detailed BIM[4]-based simulations via EnergyPlus (E+) or Integrated Environmental Solutions Virtual Environment (IES VE) that are closer to measurements. The consideration of non-linear equations, smaller time intervals (monthly/daily/hourly instead of annually) or of sector coupling between electricity and heat generation would be interesting and could also lead to more precise results. However, this would increase the computing time of the model significantly.

Since 2021, there is a new CO_2 emission pricing system in Germany with about 25 €/ton of emitted CO_2 (rising up to 55 €/ton CO_2 in 2025). This leads to increased costs of oil by about 0.8 cents/kWh and of gas by 0.5 cents/kWh and a reduction in electricity costs is planned, but not further specified yet

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[4] BIM = Building Information Modeling

[62-63]. Therefore, its effect is still unclear and cannot be considered currently, but should be taken into account in subsequent studies.

In future, the objective function of the model could be transformed into a multi-criteria problem including thermal or aesthetic comfort for example. A more complex economic objective is also possible, as described in e.g. the European Energy Performance of Buildings Directive [64], which takes into account a life cycle assessment of buildings and building components.

In a further step, the model results could be scaled up to Germany's owner-occupied residential buildings, helping to design German "Energiewende" transition paths for the SFH stock. This could be simulated for example by considering the willingness to pay or invest by different sinus milieu groups of SFH owners, neighborhood effects, regional differences in economic prosperity, and other influential factors on energy retrofit implementation. With a modified database, SFHs and funding schemes of other countries could also be analyzed with our model.

5 Conclusions

To investigate the incentive effect of the German funding system as of 2020 for energy retrofits of owner-occupied SFHs constructed in the time between 1958 and 1978, we developed an optimization model and performed a case study utilizing it. We included the funding schemes of the Kreditanstalt für Wiederaufbau banking group (KfW) and the Federal Office for Economics and Export Control (Bundesamt für Wirtschaft und Ausfuhrkontrolle (BAFA)) as well as tax benefits. Our case study uses two representative SFHs from the 1960s and 1970s show that retrofits of SFHs in Germany can significantly lower the energy demand of buildings in a financially optimal scenario for owners. Moreover, we analysed how much CO_2 can be saved with a financially optimal retrofit of these buildings from the perspective of self-using SFH owners. We found that the financial incentive effect of the German funding instruments can lead to financially optimal annual CO_2 emissions of 7-18% of the original annual emissions. Yet, it is clear that the conditions of German funding programs are not designed to maximize CO_2 savings per funded euro. The funding invested to reduce an annual ton of CO_2 ranges from 493 € to up to 3,747 € in our study. Since the KfW and BAFA programs are not only aiming at reduced energy demand/consumption, but also a means to achieve the national climate goals, it is necessary to consider an adaption of the German funding schemes focusing more on CO_2 reduction potentials instead of energy savings.

We showed that the current funding schemes lead to positive return on investments in most of the considered scenarios and investment periods of our study. From the economic perspective, the amount of available equity for retrofits investments plays a minor role. In our case study, we found that the funding programs by the KfW offer better funding options for comprehensive retrofits than tax benefits, as higher subsidies are granted with higher energy standards of the whole building.

Overall, from the theoretical perspective of our model we find that the funding conditions in Germany are already very attractive to motivate SFH owners of buildings from the 1960s and 1970s to save energy and CO_2 with comprehensive retrofits. If we consider the low rate of building retrofits in Germany (around 1%), then we can conclude that this low rate is likely not caused by the lack of attractive funding conditions for this building class.

Finally, we would like to highlight that the investigation of the funding conditions for SFHs constructed before any energy regulation standards in other European countries would be very beneficial towards helping achieve climate their goals. For this, the systematics of our simple model can be adopted and our case study program easily modified. This would also likely be beneficial for other pre-energy regulation building classes within Germany as well.

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