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Multiobjective optimisation of energy systems and building envelope retrofit in a residential community

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HIGHLIGHTS

- Simultaneous optimisation of building envelope retrofit and energy systems.
- Retrofit and energy systems change interact and should be considered simultaneously.
- Case study quantifies cost-GHG emission tradeoffs for different retrofit options.

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ABSTRACT

In this paper, a method for a multi-objective and simultaneous optimisation of building energy systems and retrofit is presented. Tailored to be suitable for the diverse range of existing buildings in terms of age, size, and use, it combines dynamic energy demand simulation to explore individual retrofit scenarios with an energy hub optimisation. Implemented as an epsilon-constrained mixed integer linear program (MILP), the optimisation matches envelope retrofit with renewable and high efficiency energy supply technologies such as biomass boilers, heat pumps, photovoltaic and solar thermal panels to minimise life cycle cost and greenhouse gas (GHG) emissions.

Due to its multi-objective, integrated assessment of building transformation options and its ability to capture both individual building characteristics and trends within a neighbourhood, this method is aimed to provide developers, neighbourhood and town policy makers with the necessary information to make adequate decisions.

Our method is deployed in a case study of typical residential buildings in the Swiss village of Zernez, simulating energy demands in EnergyPlus and solving the optimisation problem with CPLEX. Although common trade-offs in energy system and retrofit choice can be observed, optimisation results suggest that the diversity in building age and size leads to optimal strategies for retrofitting and building system solutions, which are specific to different categories. With this method, GHG emissions of the entire community can be reduced by up to 76% at a cost increase of 3% compared to the current emission levels, if an optimised solution is selected for each building category.

1. Introduction

Buildings, with their long life cycles and large share in global energy consumption [1], play an important role in recent efforts to reduce anthropogenic GHG emissions. A multitude of building-related goals for energy efficiency and GHG emission reduction in buildings have therefore been developed [2]. In Switzerland for example, the Energy Strategy 2050 policy [3] or the 2000 Watt society vision [4] identify buildings as important potential contributors in the effort to improve energy efficiency and reduce GHG emissions. These overarching policies are being combined with building-specific standards issued by the Swiss Society of Engineers and Architects (SIA), or labels such as Minergie [5] to provide policy guidance, environmental performance measures and requirements for buildings.

The ideal way to achieve these targets for existing buildings is, however, not yet clear, as one can invest either in envelope retrofit to reduce energy demands, or in more efficient and less GHG

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Nomenclature

General abbreviations

COP	coefficient of performance
D	detached building
EPS	expanded polystyrene
GHG	greenhouse gases
L	large building
MILP	mixed-integer linear program
MW	mineral wool

Variables

A_{roof}	roof area [m^2]
Cap	capacity [kW]
E	energy [kWh]
I	input power [kW]
L	load or energy demand [kW]
O	objective function [CHF or kg $CO_{2\text{-eq}}$]
P	power, flowing within the energy hub [kW]
y	binary decision variable [–]
η	efficiency [–]

Superscripts/technologies

ASHP	air source heat pump
Bio	biomass boiler
ElecHeat	electrical heating system
Grid	electricity grid
GSHP	ground source heat pump
HeatDistr	heat distribution system
HP	heat pump (ASHP or GHSP)
Oil	oil heating system
Sol	solar technologies (PV and ST)
PV	photovoltaic panels
ST	solar Thermal panels
τ	any energy conversion technology

Subscripts/energy sources and sinks

Bio	biomass (pellets)
DHW	domestic hot water
El	electricity consumption
Feedin	electricity fed back to the grid
Grid	grid electricity
i	set of energy inputs to the energy hub (biomass, solar radiation, grid electricity)
l	set of energy outputs from the energy hub (space heating, DHW, electricity for consumption, electricity feedin)
mat	any retrofit material
Oil	heating oil
PV	electricity from photovoltaic panels
ret	retrofit
s	storage (hot water tank)
SH	space heating
t	time [h]

Parameters

a	annuity factor [–]
c	costs [CHF or CHF/kWh]
f	impact factor [kg $CO_{2\text{-eq}}$/kg or kg $CO_{2\text{-eq}}$/kWh]
fc	fixed costs [CHF]
k	integer used for epsilon-constraints [$1 \ldots n-1$]
lc	linear costs [CHF/kW or CHF/m^2]
m	mass [kg]
M	large number used for binary variables [–]
n	number of intervals for epsilon-constraints
r	yearly interest rate [–]
T	lifetime [years]
ε^k	greenhouse gas limit for multiobjective optimisations

intensive energy systems [6]. On the energy demand side, improving the airtightness and insulation level of different envelope components such as windows, walls or roofs can reduce the energy demand and increase thermal comfort; energy efficient lighting systems and appliances reduce the energy demand further. On the supply side, efficiency can be further improved with state-of-the-art conversion and storage technologies including heat pumps and combined heat and power systems, or by using renewable energy with solar, wind, geothermal or biomass technologies [6].

In addition to the multitude of transformation options, the optimal strategy depends on the building type, use, age, geographical and other boundary conditions, as well as on the goals of decision makers [7].

Given the diversity of existing buildings as well as the multitude of energy supply and demand measures, a systematic approach is needed to evaluate the effectiveness of different strategies with respect to the requirements of different stakeholders [7].

Furthermore, demand and supply measures should be considered simultaneously as they are interdependent and not all equally effective. For example, retrofitting the building envelope can improve a heat pump's coefficient of performance (COP) as the necessary heating system flow temperature is reduced [8].

This contribution presents a multi-objective method to optimise retrofit and energy system transformation simultaneously, exploring cost- and GHG emission effective solutions for buildings (Section 2). We have applied our method on a case study of residential buildings in a Swiss mountain village (Section 3), leading to differentiated results in terms of building age and size, as transformation strategies are optimised for costs and GHG emissions. The single and multi-objective results as well as a possible scenario for the entire community are presented and discussed in Section 4.

1.1. State of the art and originality

Improving building energy performance with envelope and energy systems retrofit is a very active area of research. Ma et al. [7] and Hong et al. review typical building retrofit processes, commonly used technologies and design tools. Optimisation methods used for building design and retrofit are reviewed by Evins [9] and Machairas et al. [10]. The remainder of this literature review focuses on recent studies optimising building systems, envelopes and retrofit, grouping them according to the deployed optimisation method.

1.1.1. Genetic algorithms

Genetic algorithms and building simulation are commonly used to evaluate envelope retrofit and, in some cases, the replacement of building systems with respect to costs and energy or environmental objectives. Schwartz et al. [11] optimise a single building for costs and GHG emissions—considering embodied energy in retrofit materials, but exploring only two heating system possibilities parametrically. A combination of outside insulation and waste combustion district heating yielded the best performance for a

UK housing complex. Thermal comfort, quantified as Predicted Percentage of Dissatisfied (PPD), and energy consumption are added as objectives by Chantrelle et al. [12], who optimise envelope retrofit in a school building, without considering a change in energy systems. Costs, thermal comfort and primary energy are also used as objectives in a budget-constrained optimisation by Ascione et al. [13]—considering envelope retrofit and changes in heating and cooling setpoints, while keeping the same type of fossil-based heating system. A similar study by Penna et al. [14] investigates the climatic influence in Italy on the optimal envelope retrofit for primary energy, costs and comfort without changing energy sources, showing that the costs to achieve thermal comfort for a nearly Zero-Energy building increase in warmer climates. Ascione et al. [15] developed a genetic algorithm based approach to retrofit complex buildings with heating and cooling loads, optimising for costs and primary energy.

Changes in energy sources are considered by Shao et al. [16], who embed a combined energy use, cost and environmental impact optimisation into a wider design process for retrofit, but without considering a change in heat distribution systems for heat pumps and using a static energy demand simulation. Hamdy et al. [17] also consider renewable and efficient building systems and retrofit in their study, but optimise building envelope and heat recovery, energy systems and renewable energy sources sequentially.

A review on further multi-objective retrofit optimisations using genetic algorithms is given in [18].

1.1.2. Mathematical programming

Mathematical programming is commonly used as optimisation methods for buildings, including (non-)linear programming and MILP. To evaluate multiple objectives in inherently single-objective mathematical programming techniques, a weighting system is used by Diakaki et al. [19], Stadler et al. [20] and Karmellos et al. [21]. Diakaki et al. optimise building envelope retrofit and air conditioning systems for investment costs and primary energy without considering embodied energy, airtightness improvements or a change in energy sources. While Karmellos et al. include renewable energy sources, efficient lighting and appliances in their subsequent study, the building energy simulation is based on a simplified, static method. Stadler et al. introduce envelope retrofit to DER-CAM, a MILP optimisation tool to design and operate distributed energy resources. Demand reductions due to retrofit are calculated by decreasing thermal losses proportionally to U-value improvements at every time step.

The epsilon-constraint method [22] is a further possibility to create bi-criterion optimisations with mathematical programming. It is combined with a MILP by Antipova et al. [23] to optimise retrofit and solar panels for costs and environmental impact, but with a simplified Heating Degree Day energy demand evaluation which is embedded in the optimisation. Bayraktar et al. [24] use a simplified demand model in conjunction with an energy hub framework to optimise building systems and retrofit for costs and energy demand. Schütz et al. [25] optimise residential building retrofit for costs and GHG emissions in an epsilon-constrained optimisation, modelling energy supply technologies and building energy demands as a MILP. Although this approach relies on a linearized, static demand model, it allows for simultaneous optimisation of individual building envelope components and energy systems.

1.1.3. Optimisation at district and urban level

While the previously mentioned studies optimise individual or a small number of buildings, Jennings et al. [26] use MILP to optimise retrofit and energy systems for costs and GHG emissions at an urban level, but with simplified energy demand models to reduce the computational effort. Mauro et al. [27] developed a tool to optimise retrofit and building systems sequentially and with a typical building approach. Retrofit is optimised for costs, thermal comfort and energy demand, while building systems and renewable energy sources are optimised for costs and primary energy.

2. Methods and tools

In this contribution, building energy systems and envelope retrofit are optimised simultaneously in a bottom-up approach. Dynamic building energy demand simulation is combined with a MILP optimisation to select retrofit strategies, and size and simulate the operation of different types of energy systems. Interactions between retrofit and building systems, such as the need to replace the heat distribution system for low-temperature heating technologies at low retrofit levels, are taken into account. The life cycle GHG approach includes embodied GHG emissions in retrofit materials, and differentiates between photovoltaic (PV) and grid electricity impacts for all electric conversion systems, including heat pumps. Promising retrofit and energy system strategies are explored by scaling typical building strategies to the neighbourhood level. The proposed method can be divided into four steps, as shown in Fig. 1.

Initially, a building analysis is performed to categorise all considered buildings in terms of age, size and other main characteristics such as their current energy systems and retrofit state. Typical buildings are identified and selected, and plausible retrofit scenarios are defined for each typical building. In contrast to an approach where every building in a community or town is simulated and optimised, this approach saves time and computational effort as buildings within a category should be very similar in critical characteristics such as age, size, use or current energy systems [28]. Selection and categorisation depends on the considered case study; therefore, the process is described in the case study (Section 3.1).

In a second step, the electricity, space heating and domestic hot water (DHW) demands are simulated for every typical building and retrofit scenario with a dynamic building energy simulation tool.

Third, the resulting demand profiles are used as inputs for a multi-objective energy hub optimisation, which determines the preferred retrofit scenario and selects, sizes, and defines operating strategies for energy conversion and storage technologies to meet the demands. Considered technologies include heat pumps, solar panels, biomass and oil boilers and thermal storage, and life cycle costs and GHG emissions are used as objectives.

Finally, a promising transformation strategy is selected for each typical building and scaled up to the village level to study possible implications for the community.

The individual steps are described in more detail in the following sections.

2.1. Energy demand simulations

Based on geometrical data, locations, and typical construction types and materials for different historical periods, buildings are modelled in DesignBuilder 4.2 [29] and simulated with EnergyPlus 8.1 [30]. Operational parameters such as occupancy, heating setpoints, DHW, lighting, and electricity demands are taken from standards issued by the Swiss Association of Engineers and Architects SIA [31]. Several retrofit scenarios are considered for each building, while taking the constraints imposed by historical protection into account. As the impact of envelope retrofit on the outside appearance of protected buildings must be minimised, wall insulation is applied on the inside, while windows are assumed to be replaceable.

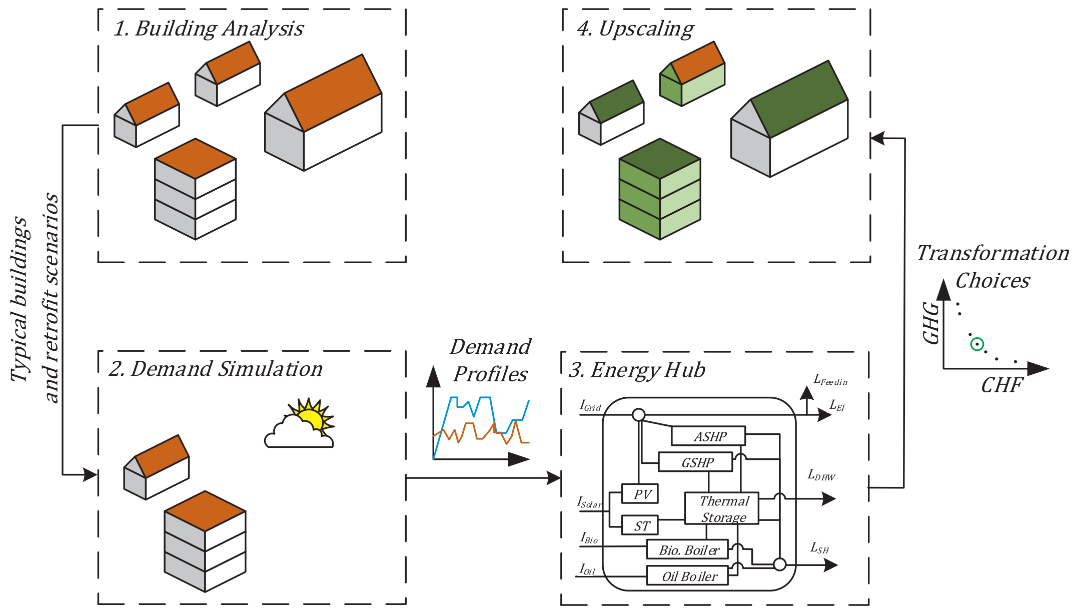

Fig. 1. Schematic of the proposed method.

Space heating and electricity demands for every building and retrofit option are simulated in hourly resolution for a year. Additionally, EnergyPlus computes the incident solar radiation on south, southeast or -west facing roof areas. As the DHW demands by SIA are given as daily totals, DHWcalc 1.10 [32] is used to calculate hourly DHW consumption profiles stochastically. Energy demand and solar radiation profiles are used as inputs for the subsequent energy hub optimisation.

Cooling is not considered, as none of the case study buildings are equipped with cooling systems.

2.2. Multi-objective energy hub optimisation

While the energy hub was originally developed as a generic framework for multi-energy system optimisation at different scales [33], it has since been applied to building and urban energy system in numerous studies [34]. Although energy hubs can be used for energy system design or operational problems separately, an operational optimisation can be nested in a design problem according to the method presented by Mavromatidis et al. [35]. In this study, an energy hub optimisation framework is used to select, size and simulate the operation of the best performing system from the following list of considered energy conversion technologies:

– Air (ASHP) and ground source heat pumps (GSHP).
– Biomass pellet and oil boilers.
– Photovoltaic (PV) and solar thermal (ST) panels.

An additional decision variable within the energy hub optimisation is the retrofit scenario, that changes the space heating demand of each building.

Every building is assumed to have a water tank for DHW and space heating, with a fixed size depending on the number of occupants.

An overview of the energy hub applied to each building is given in Fig. 2. It takes the electricity, DHW and space heating loads L as inputs. As outputs, the energy hub optimisation computes the optimal size of each technology with a bold outline in Fig. 2, all energy flows within the system as well as the necessary grid electricity, biomass and oil energy inputs I to meet the demands. As the coefficient of performance (COP) of heat pumps is highly dependent on the flow temperature, heat flows are differentiated by temperature level, with 30–40 °C for space heating and 50–70 °C for DHW.

The energy hub modelling equations contain only linear constraints and objective functions, as well as continuous and binary variables. Therefore, the energy hub optimisation is programmed as a MILP, using the AIMMS 4.4.2 [36] interface to the CPLEX 12.6.1 [37] solver. As this study focuses on optimal building design, transients in energy conversion, operational constraints and effects such as variable conversion efficiencies, minimum run-times or temperature-dependent storage charging limitations are neglected. Modelling such off-design characteristics was found to increase computational effort significantly, with a very small influence on optimal system design [38].

2.2.1. Modelling equations

Energy balances are used to relate the inputs and outputs of all conversion technologies τ at each time step t, and are described in Eqs. (1) and (2) for grid electricity, biomass and oil, solar power, both air and ground source heat pumps, and the biomass and oil boilers. Superscripts identify technologies, while subscripts are used for energy sources, time t and other identifiers. I denotes an input energy flow in the set of all energy inputs i, L an output or load energy flow in the set of loads l, and P is used for energy flows within the hub. Cap refers to capacities, η to conversion efficiencies. In Eq. (1), input electricity, biomass, heating oil and solar radiation powers are set equal to the sum of all systems and uses that the energy can flow to. S denotes the thermal storage.

$$I_{i,t} = \sum_{\tau,l} P^{\tau}_{i,l,t} + \sum_{\tau} P^{\tau}_{i,s,t} \quad \forall t, i \tag{1}$$

A further energy balance is applied to all loads, which can be fed either by a conversion technology or from storage in the case of space heating (SH) and DHW. Constant efficiencies η relate input to output energy flows for all technologies.

$$L_{l,t} = \sum_{\tau,i} \eta^{\tau}_{l} * P^{\tau}_{i,l,t} + P_{s,l,t} \quad \forall t, l \tag{2}$$

The thermal storage energy balance in Eq. (3) is defined such that the change in energy content between time steps $t-1$ and t is equal to the energy input minus the energy output from the storage. Eq. (4) enforces that the storage is empty at the first time step.

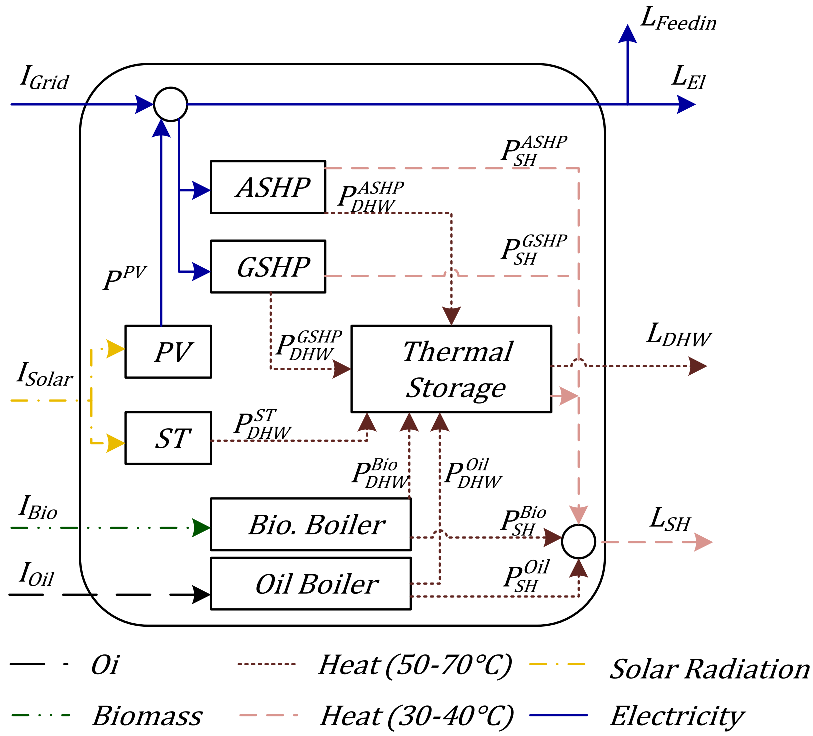

Fig. 2. Energy hub layout.

$$E_t = E_{t-1} + \sum_{\tau} \eta_s^{\tau} P_{i,s,t}^{\tau} - 1/\eta_s \sum_{l} P_{s,l,t} \quad \forall t \tag{3}$$

$$E_t = 0, \quad t = 0 \tag{4}$$

In conjunction with the objective functions, a second category of constraints is used to determine the capacity of all energy conversion technologies, which limits the sum of all output energies i to the capacity of the technology τ. Eq. (5) ensures that the output energy never exceeds the technology capacity, while the optimisation algorithm tries to minimise the capacities due to the capacity dependent costs in the objective function.

$$\sum_{i} (P_{i,s,t}^{\tau} * \eta_s^{\tau} + \sum_{l} P_{i,l,t}^{\tau} * \eta_l^{\tau}) \leqslant Cap^{\tau} \quad \forall t, \tau \tag{5}$$

As the capacity of solar technologies is expressed as collector area, their output power is limited by the product of available solar radiation, efficiency and capacity in Eq. (6), where sol is the set of solar technologies (PV and solar thermal).

$$P_t^{sol} \leqslant Cap^{sol} * \eta^{sol} * I_{solar,t} \quad \forall t, sol \tag{6}$$

Furthermore, the storage capacity and available roof area constrain the energy in the storage tank (Eq. (7)), and the area for possible solar installations (Eq. (8)) respectively.

$$E_t \leqslant E_{Max} \tag{7}$$

$$\sum_{sol} Cap^{sol} \leqslant A_{Roof} \tag{8}$$

To impose a fixed cost and minimum capacity in the objective function as soon as a technology is installed, each technology has an associated binary variable y^{τ}, which determines whether a technology is installed ($y^{\tau} = 1$) or not ($y^{\tau} = 0$). Therefore, a "Big-M" constraint is used in Eq. (9) to fix the binary variable, where M should be a sufficiently large number. Eq. (10) enforces minimum capacities as soon as a technology is chosen.

$$Cap^{\tau} \leqslant y^{\tau} * M \quad \forall \tau \tag{9}$$

$$Cap^{\tau} \geqslant y^{\tau} * Cap_{Min}^{\tau} \quad \forall \tau \tag{10}$$

A further set of binary variables y^{ret} is used to select a retrofit scenario or the base case without retrofit, which leads to a different set of space heating loads. Eq. (18) ensures that one retrofit scenario is chosen, as exactly one of the binary variables y^{ret} must be 1 while the others are 0 to make the sum equal to 1. Eq. (19) assigns the correct space heating load to L_{SH}.

$$\sum_{ret} y^{ret} = 1 \tag{11}$$

$$L_{SH,t} = \sum_{ret} y^{ret} * L_{SH,t}^{ret} \quad \forall t \tag{12}$$

As the heating distribution system has to be changed for certain conditions discussed in Section 3.3, a binary variable $y^{HeatDistr}$ is introduced, which is 1 if the building is either currently heated with electric resistance heaters or if an oil heating is replaced by an ASHP or a GSHP without retrofitting the façade or the whole building. Eq. (13) sets $y^{HeatDistr}$ to 1 if the building is currently heated with electricity, as the binary parameter $y^{ElecHeat}$ is 1 if the building is currently heated with electricity and 0 otherwise.

$$y^{HeatDistr} \geqslant y^{ElecHeat} \tag{13}$$

The right hand side of Eq. (14) is positive if a heat pump is chosen ($y^{ASHP} + y^{GSHP} \geqslant 1$) and the retrofit state is less than façade or whole building ($\sum_{ret=None}^{Window\,Target} y^{ret} = 1$), which is the condition for oil heated buildings to have their heat distribution system replaced. "Window Target" is the last retrofit scenario necessitating a change in heat distribution system (see Section 3.2). As $y^{HeatDistr}$ is a binary variable, the scaling factors 1.5 and 2 are used to ensure that the right hand side of Eq. (14) is never larger than 1, but positive as soon as the abovementioned conditions are met.

$$y^{HeatDistr} \geqslant \left(\sum_{ret=None}^{WindowTarget} y^{ret} + y^{ASHP} + y^{GSHP} - 1.5 \right) \Big/ 2 \tag{14}$$

Finally, simultaneous grid electricity import and feed-in is prevented with a binary variable $y_{Grid,t}$, equal to 1 if power is consumed from the grid, zero otherwise, using Big-M constraints for grid electricity.

$$I_{grid,t} \leqslant y_{Grid,t} * M \tag{15}$$

$$L_{Feedin,t} \leqslant (1 - y_{Grid,t}) * M \tag{16}$$

2.2.2. Objective functions

Annualised costs and life cycle GHG emissions are considered as objective functions. In the cost objective function O_1 in Eq. (17), subsidised investment costs are split into fixed fc^{τ} and capacity dependent linear costs lc^{τ}, whereas all input energy carriers I are multiplied with their costs. Retrofit costs c^{ret} are added as fixed costs for the chosen retrofit scenario. $y^{HeatDistr}$ imposes the fixed costs for the heat distribution system change if necessary.

$$O_1 = \sum_{\tau} \frac{fc^{\tau} * y^{\tau} + lc^{\tau} * Cap^{\tau}}{a^{\tau}} + \sum_{t} (I_{Grid,t} * c_{Grid} + I_{Bio,t} * c_{Bio} - L_{Feedin,t} * c_{Feedin}) + \sum_{ret} (y^{ret} * c^{ret}) / a^{ret} + y^{HeatDistr} * c^{HeatDistr} / a^{HeatDistr} \tag{17}$$

All investment costs are annualised using the equivalent annual cost method [39], considering their lifetimes T and interest rates r:

$$a = \left(1 - \frac{1}{(1+r)^T} \right) \Big/ r \tag{18}$$

As life cycle GHG emissions are evaluated per unit of delivered final energy, or mass-specific for retrofit materials, the environmental impacts are calculated in Eq. (19) by multiplying the impact factors f_i with the conversion outputs $P_{i,t}^{\tau} * \eta_i^{\tau}$, where $P_{i,t}^{\tau}$ is the input power from energy source i to technology τ at time t, and η_i^{τ} the conversion efficiency. Likewise, the masses of used retrofit materials mat are multiplied with their impact factors f_{mat}. T refers to the lifetime for retrofit.

$$O_2 = \sum_{t} \sum_{i} P_{i,t}^{\tau} * \eta_i^{\tau} * f_i + \frac{\sum_{ret} y^{ret} * \left(\sum_{mat} m_{mat}^{ret} * f_{mat} \right)}{T} \tag{19}$$

2.2.3. Epsilon-constraint multi-objective method

Introduced by Haimes et al. [22], the epsilon-constraint method enables a multi-objective optimisation within a single objective framework. Two initial single objective optimisations, one to minimise cost (O_1) and one to minimise GHG emissions (O_2), determine the corner points of the pareto curve with maximum GHG emissions GHG_{max} when minimising O_1, and minimum GHG emissions GHG_{min} when minimising O_2. The difference between GHG emissions of the two initial solutions $GHG_{max} - GHG_{min}$ is divided into n intervals, and a single objective optimisation is run for each interval. GHG emissions are limited to intermediate levels ε^k, which increase the allowable GHG in steps of $(GHG_{max} - GHG_{min})/n$ by increasing k from 1 to $n-1$.

$$\textit{minimise } O_1 \textit{ subject to } O_2 \leqslant \varepsilon, \quad \varepsilon \in \{\varepsilon^1, \varepsilon^2, \ldots, \varepsilon^{n-1}\} \tag{20}$$

$$\varepsilon^k = k * \frac{GHG_{max} - GHG_{min}}{n} + GHG_{min}, \quad k \in \{1, 2, \ldots, n-1\} \tag{21}$$

In the case study, each building is optimised in 2 initial and 68 epsilon-constrained runs.

2.3. Upscaling of transformation strategies

To explore the implications of applying a certain set of retrofit and building system interventions for the community, solutions from typical buildings are scaled up to the community level. The area-specific costs, fuel uses and GHG emissions of every typical building are multiplied by the floor area of all buildings represented by this typical building. In contrast to an approach where every building in the community is simulated and optimised individually, this method saves computational and parametrisation effort [28].

As the multi-objective optimisation yields a multitude of transformation options for each typical building, there would be a range of different possible choices at the community level as well. As a preliminary approach to demonstrate the principle, the solutions to be scaled up to the community level are manually chosen within this study. More refined approaches such as a global optimisation at community level, taking GHG emission targets, budget constraints and limited resource availability explicitly into account are currently being investigated in a subsequent study.

3. Case study

Residential buildings in Zernez, which started a project to reduce its building induced GHG emissions and become energy self-sufficient [40–42], are used as a case study. Located in south-eastern Switzerland at an altitude of 1474 m above sea level, Zernez has a population of 1150 inhabitants and approximately 200 residential buildings. In 2012, a database containing building occupancy, use, geometrical and construction data was compiled for all buildings in Zernez, which is used to categorise and model the buildings for the demand simulation. As simulating and optimising every building in Zernez would not be efficient due to similarities between buildings of the same age, size or construction type, an archetype approach is used.

3.1. Building categorisation and selection

The categorisation and selection of typical buildings is based on a previous study [43], which compared the energy demand prediction accuracy of individual building simulation with a typical building approach. It was found that building use, construction time, size, number of inhabitants and heating system type have the highest influence on energy demands in Zernez. Therefore, the existing residential buildings are categorised in terms of their age, size and current heating system in this study. Construction years are split into the following categories:

- Before 1900,
- 1900–59,
- 1960–79,
- 1980–99.

Buildings built after 2000 are not optimised, as their insulation levels are close to today's standards already.

As an indicator for building size, this study differentiates between detached buildings with 1 housing unit (D), semi-detached (SD) and large buildings (L) with 3 or more housing units, with mean inhabited floor areas of 296 m^2, 430 m^2 and 629 m^2 respectively.

In this study, 11 typical buildings, one for each age and size category with the exception of semi-detached buildings built in

Table 1
Total inhabited floor areas per age, size and heating system category.

	Total floor area heated by oil/electricity [m^2]		
Age category	Detached (D)	Semi-Detached (SD)	Large (L)
<1900	823/3543	279/4302	20,207/8434
1900–59	1554/0	–	440/483
1960–79	2581/4060	916/0	8600/0
1980–99	3520/4582	1106/1934	6120/3627

Table 3
Assumed air change rates (ACR).

Age category/retrofit level	ACR [1/h]
Before 1980 – no retrofit	0.7
1980–1999 – no retrofit	0.6
Roof Limit and Roof Target	0.6
Windows Limit and Windows Target	0.6
Façade Limit and Façade Target	0.5
Whole building (SIA 380/1 limit)	0.4
Whole building (SIA 380/1 target)	0.3

1900–59 which do not exist in Zernez, are selected and referred to with the following nomenclature: "Size identifier - Age identifier". D-1900 for example identifies a detached building built before 1900, L-60-79 a large building between 1960 and 1979. Table 1shows the average and total floor areas in each category.

The vast majority of buildings in Zernez is currently heated with oil or electric resistance heaters, often complemented with wood stoves. As oil and electric heating systems are distributed evenly across all buildings, 6 electrically and 5 oil heated buildings are selected.

3.2. Demand simulation data

Building geometries are based on the 2012 survey and a 1:25,000 map [44], whereas the wall, roof and floor constructions are taken from an overview of historical construction types [45] and their insulation thicknesses adapted to match U-Values used in a previous study [43]. Table 2 summarises the assumed U-Values together with the two possible retrofit levels for each component, the SIA 380 limit and target U-Values which correspond to the current Swiss building standard [46].

While the buildings built after 1960 are not historically protected and can therefore be retrofitted with typical insulation materials such as expanded polystyrene (EPS, used in this study) or mineral wool on the outside, all older buildings are protected, which leads to the assumption that they can only be insulated inside. Polyurethane foam is chosen as an internal insulation material for this study, as its low thermal conductivity reduces the loss of habitable space compared to EPS or mineral wool.

Each building built before 1980 is modelled in nine configurations, where the following envelope components are retrofitted to SIA 380 limit and target values. Limit values have to be met and should be easily reached with current technologies, while target values can be reached and even outperformed with current technologies, even though the required solutions may not be economically viable or feasible in some cases according to SIA. The considered cases are:

- Original heating system – no retrofit, and the current heating system is kept.
- Base case – no retrofit is performed, but the heating system is optimised.
- Roof – insulated to SIA380 limit or target.
- Windows – insulated to SIA380 limit or target.
- Façade – windows and walls insulated to SIA380 limit or target.
- Whole building – all components are retrofitted to SIA380 limit or target.

In the age category of 1980–99, roof retrofit to SIA limit values is not considered, as this scenario would require less than 3 cm of additional EPS or mineral wool (MW), which is deemed unrealistic due to the costs.

As retrofit can and should improve airtightness, this study assumes different air change rates depending on building age and retrofit scenario, as shown in Table 3. Limits for airtightness and minimum fresh air per person from SIA 180 [47] are taken into account.

Internal gains, heating set points, lighting, electricity and occupancy profiles are based on SIA 2024 [31], with a distribution of 80% living space and bedrooms, 10% kitchen and 10% bathrooms for all buildings.

The EnergyPlus simulation is carried out using weather data from 2002 in Scuol, a neighbouring village with similar climatic conditions as Zernez, since no weather data are available for Zernez. Scuol has an average temperature of 4.82 °C and a global horizontal irradiation of 1064 kWh/m^2/year [48].

3.3. Cost and GHG emission data

Investment costs for all building energy systems are assumed to depend linearly on the nominal conversion capacity. By performing a linear regression on investment costs for commercially available systems by Swiss suppliers, fixed and capacity dependent costs are calculated. They include the equipment, installation, the control system and connections to existing heat distribution systems, and are summarised in Table 4. However, there is a considerable cost uncertainty regarding the connection of heat pumps to existing oil- or electricity-based distribution systems, as heat pumps usually require a low temperature radiator design. While replacing radiators with floor heating is not common in Switzerland for cost reasons, solutions such as deploying high temperature heat pumps (ca. 60 °C outlet temperature), larger radiators or active convectors have been proposed. Changing the heat distribution system is taken into account by imposing an additional area-specific cost, if one of the following conditions is met:

Table 2
U-Value assumptions.

	U-Value [W/(m^2 K)]			
Age category or retrofit level	Walls	Roof	Ground floor	Windows
Before 1900	1.54	0.79	1.42	2.5
1900–59	2.04	1.29	1.18	2.5
1960–1979	1.78	1.38	1.95	2.5
1980–1999	0.53	0.33	0.56	2.5
SIA 380 Limit	0.25	0.25	0.3	1.3
SIA 380 Target	0.15	0.15	0.2	0.9

Table 4
Energy system parameters including unsubsidised fixed and capacity dependent costs, lifetimes, minimum plant sizes and efficiencies. Heat pump efficiencies are different for space heating (SH) and DHW.

Technology	Fixed cost [CHF]	Linear cost [CHF/kW]	Lifetime [years]	Minimum size [kW]	Efficiency
Biomass boiler	27,800	860	20	10	0.85
GSHP	20,000	2380	20[a]	5	4 (SH) 2.75 (DHW)
ASHP	18,300	1020	20	5	3 (SH) 2 (DHW)
ST	4000	1000 [CHF/m^2]	25	4 [m^2]	0.7
PV	900[b]	400 [CHF/m^2]	30	5 [m^2]	0.15
Electrical heating	14,600	730	30	–	1
Oil boiler	26,600	570	25	10	0.85
Heat distribution system	–	100 [CHF/m^2]	25	–	–

[a] The GSHP borehole, which is assumed to make up 45% of the entire system cost, is discounted over 50 years.
[b] For protected buildings, built-in PV modules with fixed costs of 3000 CHF are considered.

Table 5
Life cycle GHG factors and fuel prices.

Technology/energy carrier	GHG factor [kg $CO_{2\text{-eq}}$/kWh]	Fuel costs [CHF/kWh]
Biomass (wood pellets)	0.05514	0.1
GSHP (Grid/PV)	0.05891/0.04015	
ASHP (GRID/PV)	0.08180/0.05566	
Solar thermal	0.02779	
PV	0.07519	
Grid electricity	0.14840	0.2
Electricity feed-in	−0.0732	−0.15
Heating oil	0.34064	0.09

Table 6
Densities and embodied GHG in retrofit materials for production and disposal.

Component or material	Density [kg/m^3]	Embodied GHG [kg $CO_{2\text{-eq}}$/kg]
Expanded Polystyrene	27.5	7.53
Mineral Wool	96	0.783
Glazing (SIA 380 Limit)	–	47.7 [kg $CO_{2\text{-eq}}$/m^2]
Glazing (SIA 380 Target)	–	57.6 [kg $CO_{2\text{-eq}}$/m^2]

1. The building is currently heated with electric resistance heaters and therefore does not have a central heat distribution system.
2. The building is currently heated with oil, is not retrofitted to façade or whole building levels, and changes to an ASHP or GSHP for heating.

As biomass boilers can achieve the same flow temperatures as oil boilers, it is assumed that the distribution system can remain unchanged. Due to the significant reduction in heating demand when retrofitting the façade or whole building, it is assumed that the existing heat distribution system remains unchanged, since the reduced demands can be met even though heat pumps produce heat at lower temperatures than oil boilers.

Retrofit costs are calculated with a Swiss building energy and retrofit analysis tool [49] and are discounted over a lifetime of 50 years. The costs for inside insulation are composed of a material price based on commercially available polyurethane products, and assumed installation costs of 140 CHF/m^2. Retrofit and building energy system subsidies by the Canton of Graubünden [50], and a one-time payment by the Swiss federal government [51], are taken into account. Graubünden subsidises both energy efficient heating systems such as heat pumps or biomass boilers as well as retrofit of façade, floor or roofs, and the envelope retrofit subsidies are doubled if the entire building is retrofitted.

Life cycle GHG factors are taken from ecoinvent [52] for energy, and a Swiss database for embedded carbon in building materials [53], also based on ecoinvent. In this study, PV power fed back to the grid is rewarded by the difference in GHG between the Swiss consumer mix and PV production. Table 5 summarises the carbon factors and fuel costs for energy delivered from all considered technologies.

GHG emissions for retrofit, summarised in Table 6, only include the embedded GHG in the materials for production and disposal without considering transport and installation, and are divided by the lifetime of 50 years in the cost function.

4. Results and discussion

Results of the energy demand simulations (Step 2 of the method described in Section 2) are discussed in Section 4.1. Single- and multi-objective results of the energy hub optimisation (Step 3) are presented in Sections 4.2 and 4.3. The implications of selecting a particular set of solutions for the entire community (Step 4) are discussed in Section 4.4. Due to site-specific inputs such as climate and cost data, the case study results should not be generalised beyond alpine regions with a similar price structure.

4.1. Energy demands

In Fig. 3, the simulated yearly heating demands are shown. For all buildings, the heating demand is reduced by at least 50% as soon as the façade or whole building is retrofitted. At maximum retrofit, the simulated space heating demand of most buildings complies with the heating load requirements of the Minergie-P standard [5], which certifies buildings with very low energy demands in Switzerland. The effectiveness of reducing heating demands follows the order in which the measures are listed in Fig. 3, with the exception of buildings D-00-59 and L-00-59 which have inhabited roof spaces, and buildings D-60-79, SD-80-99 and L-80-99, whose initial window and roof insulation level is high enough such that façade target retrofit reduces the energy demand more than whole building limit retrofit.

As the room electricity demands are based on standards, the yearly room electricity per unit area, as shown in Fig. 4, is the same for all buildings. Lighting electricity, however, is calculated based on a target illuminance level and therefore depends on the amount of available daylight, which is influenced by building geometry and orientation, shading and window-to-wall ratios and therefore building dependent. The solid, dotted and dashed line indicate the standard, minimum and maximum consumption given in the same standard. While the simulated energy demand of most buildings is at the lower limit, the lighting demands of buildings D-60-79 and D-80-99 are higher than the standard value, which is related to their northern exposure and shading by other buildings.

As validation, the simulated energy demands of the current base case without retrofit are scaled up to the community level

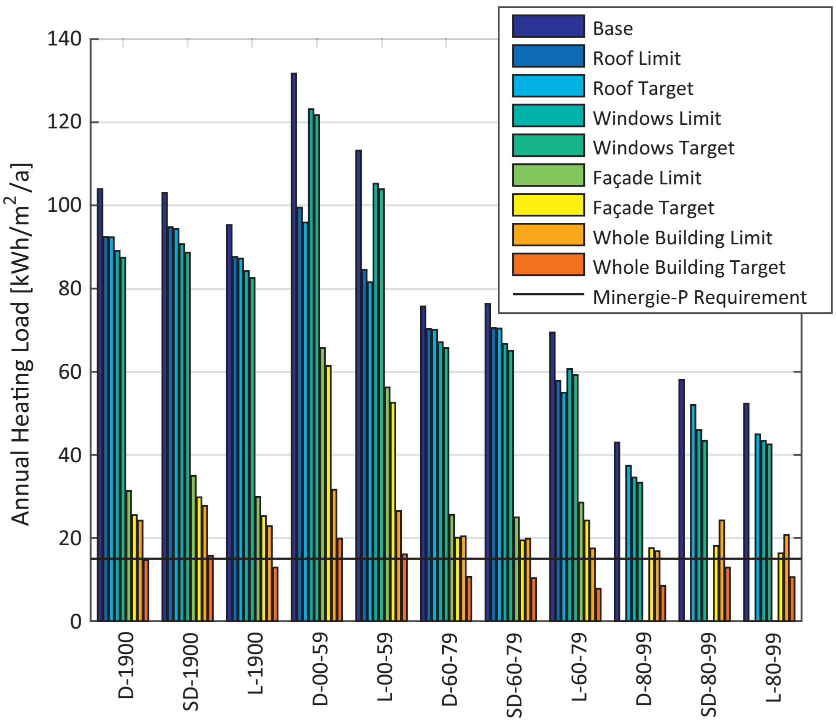

Fig. 3. Simulated heating demands of all buildings. Bars are grouped per building, colours identify retrofit scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

using the method described in Section 2.3, and compared to measured data. The simulation overestimates yearly electricity demands by 35% and underestimates the combined DHW and space heating demands by 9.6%, yielding a 0.4% overestimation of total energy demands. As the allocation of electricity between heating and direct use in electrically heated buildings introduces further inaccuracies, the total energy demand prediction might be more relevant to validate the simulation.

4.2. Single objective optimisation

Fig. 5 shows the single objective cost optimisation for building D-60-79 as an example for an oil heated building with relatively low initial insulation levels. Shifting from the current configuration ("Original Heating system") to the first optimised case ("Base", which has the same energy demand with a cost-optimised energy system) introduces some electricity cost savings due to the PV system which covers the entire south-facing roof space. For all other retrofit scenarios however, retrofit investments outweigh the associated savings in energy costs and heating system. As soon as the façade is retrofitted, an ASHP is installed, which is the cheapest solution for medium to high energy demands if the heat distribution system is not changed.

The corresponding GHG emissions in Fig. 5 show that costs and GHG emissions are conflicting objectives for this optimisation. Due to the reduction in heating energy demand, GHG emissions monotonously decrease with increasing retrofit level, with a sharp drop as soon as the façade is retrofitted.

As the Canton of Graubünden doubles its retrofit subsidies as soon as the entire building is retrofitted, the total costs of a whole building retrofit to SIA380/1 limit values are lower than for a façade retrofit to SIA 380/1 target values.

When optimising the same building for GHG emissions as depicted in Fig. 6, a combination of biomass and PV panels is found. Switching from oil to biomass in the base case without retrofit reduces the GHG emissions by 80%, while a whole building SIA380/1 limit retrofit decreases GHG by 88% compared to the oil heating system, increasing the cost by 158% compared to the original configuration.

An overview of all single objective cost optimisations is given in Fig. 7. The costs are averaged across all size categories and split into retrofit, systems investment and energy costs. To show the influence of federal and cantonal subsidies, unsubsidised total costs are outlined as well.

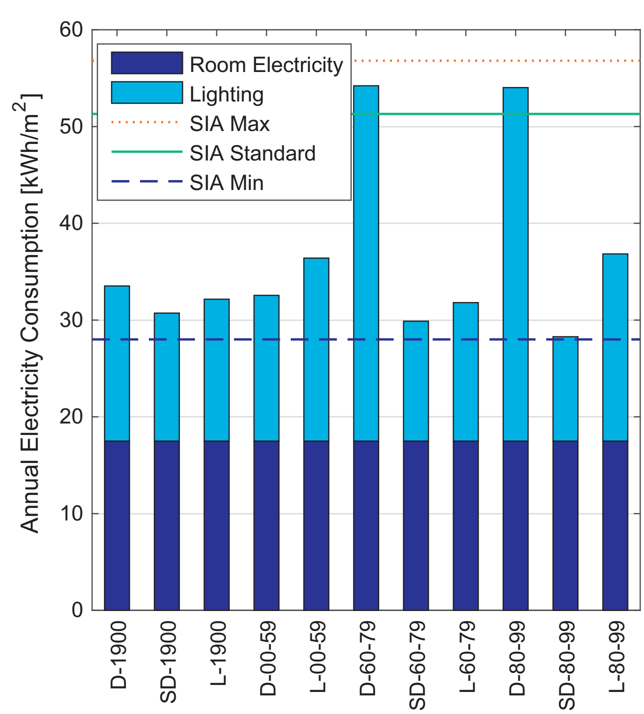

Fig. 4. Simulated electricity demands for every typical building.

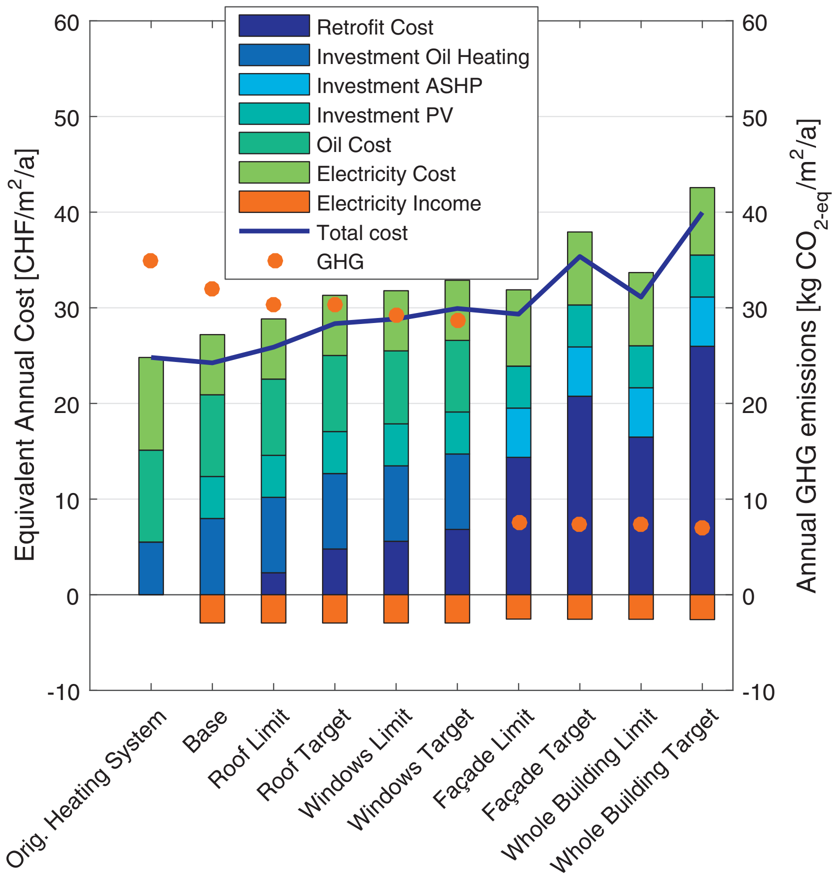

Fig. 5. Single-objective subsidised cost optimisation results for all retrofit scenarios of building D-60-79. The line and dots identify total costs and GHG emissions, bars show the cost breakdown for each technology and retrofit.

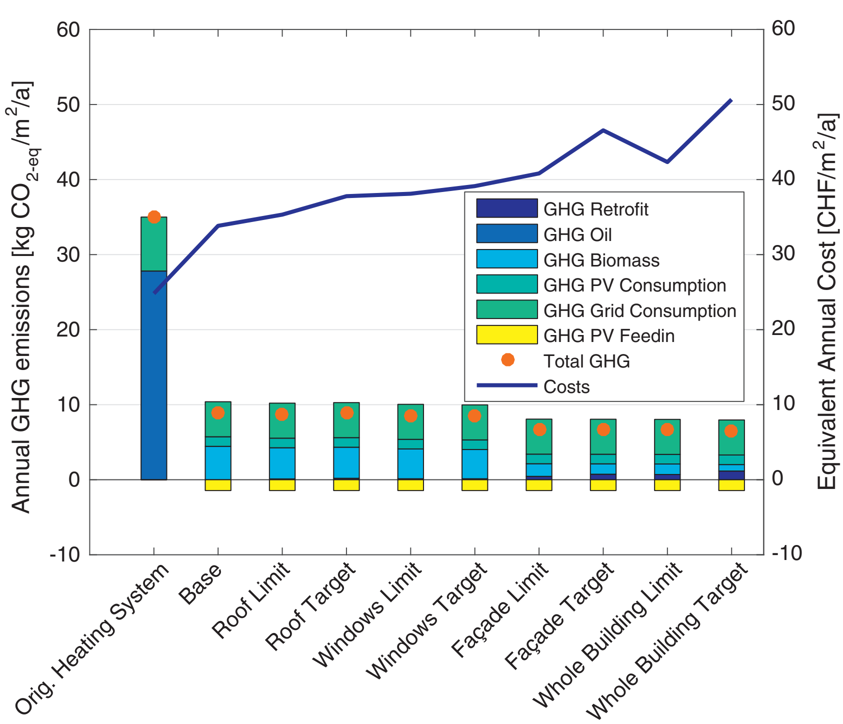

Fig. 6. Single-objective GHG optimisation results for all retrofit scenarios of building D-60-79.The line and dots identify total costs and GHG emissions, bars show the GHG emission breakdown for each technology and retrofit.

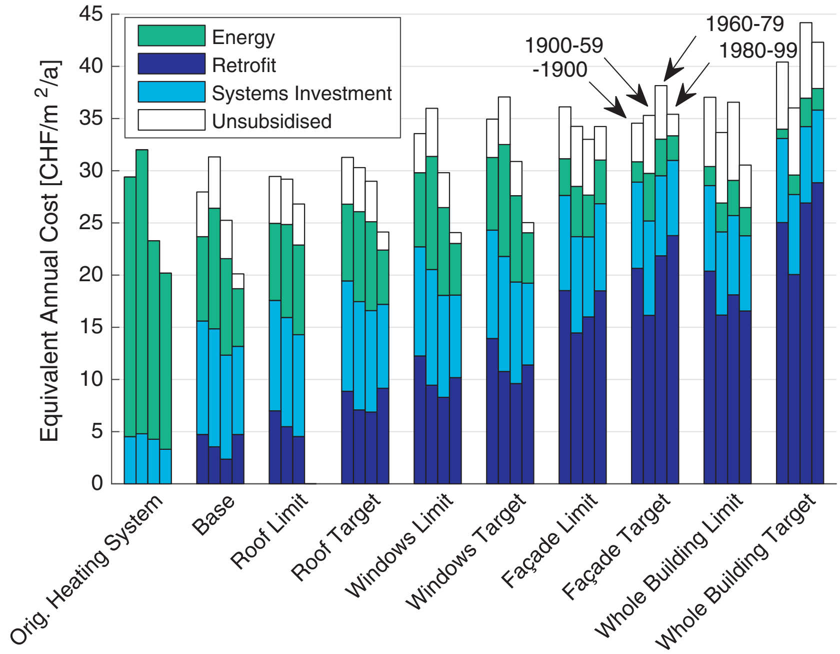

Fig. 7. Equivalent Annual costs of the single-objective cost optimisation for all retrofit scenarios, averaged per age category.

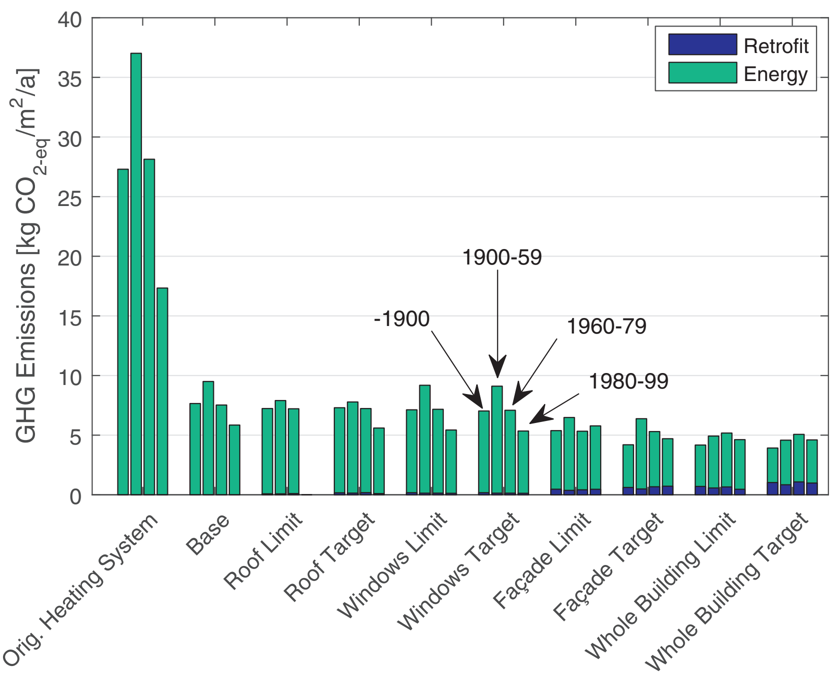

Fig. 8. Single-objective GHG optimisation results for all retrofit scenarios, averaged per age category.

Results of the cost optimisation suggest that up to window retrofit, the total costs reflect the initial insulation levels of the buildings listed in Table 2, where the 1900–59 category has the worst and the 1980–99 buildings the best U-value, resulting in the highest average costs for buildings in the 1900–59 category and lowest costs for the 1980–99 buildings. For façade and whole building retrofit however, the retrofitting costs for buildings before 1959 are lower due to the inside insulation, compared to newer buildings which are insulated on the outside. Although the inside insulation costs are estimated based on commercially available materials and installation offers, they can vary significantly for each building.

For all age categories, costs tend to increase as a function of the retrofit level, as energy systems cannot be significantly downsized, and the energy cost savings are outweighed by the investments in retrofit.

In terms of building systems, oil heated buildings typically keep their original heating system until the façade or whole building is retrofitted, while electrically heated buildings immediately change

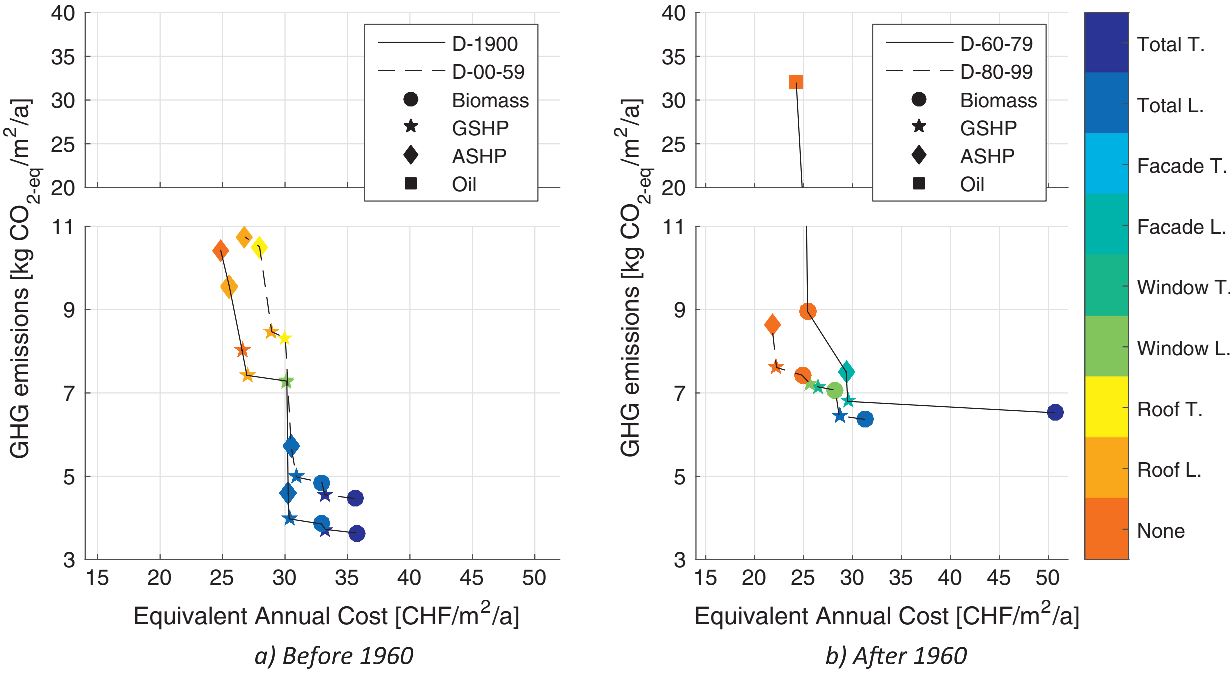

Fig. 9. Cost - GHG multi-objective pareto fronts for all detached buildings. L and T abbreviate retrofit to limit and target U-Values.

to ASHP, or GSHP for smaller demands at high retrofit. The entire south, south-east or south-west facing roof area is used for PV in all buildings.

Fig. 8 shows the GHG optimisation results as averages per age category. When minimising GHG, all buildings use a pellet heating system combined with maximised PV, and the most significant change in environmental impact is observed when switching from the original heating system to biomass in the base case.

4.3. Multi-Objective optimisation

Results of the multi-objective cost-GHG optimisation are shown per size category in Figs. 9–11. Buildings are identified by the line style connecting the pareto optimal points, marker shapes identify the selected heating system, while the colours identify the retrofit scenario.

While the results are different for every building, some general trends can be observed. PV is always maximised as this technology is both cost-effective and reduces the GHG emissions compared to grid electricity for the assumed parameters. Competing for the available roof space with PV, solar thermal panels are not used as they cost more than PV in Switzerland, mainly due to the necessity to connect them to the existing heat distribution system, and because biomass or heat pump technologies provide alternative ways to decarbonise heat, while PV is the only possibility in this optimisation to save GHG emissions related to electricity.

As retrofit and technology choice combinations are limited, the pareto fronts consist of less than 15 distinct solutions per building, often with sharp slope changes, indicating that the costs to reduce GHG emissions further can change dramatically depending on the location on the pareto front.

4.3.1. Heating systems

Due to the costs of replacing or installing a heat distribution system discussed in Section 3.3, there is a systematic difference between electrically and oil heated buildings.

In buildings currently heated with electricity, a centralised heat distribution system has to be installed in any case. Following the optimisation, heating systems are always selected in the following order; from ASHP, which minimise cost, via GSHP to biomass, which minimises GHG emissions. This ranking is observed several times per building, typically for the following sets of retrofit scenarios:

- Low retrofit (none to window target).
- Medium retrofit (window limit to whole building limit).
- Maximum retrofit (whole building target).

For maximum retrofit, only GSHP and biomass systems are chosen, as GHG emissions are highly restricted for this set of solutions.

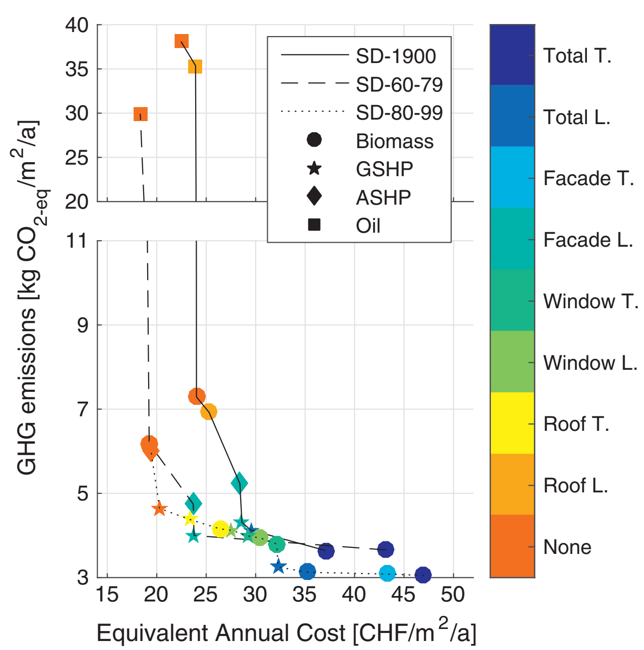

Fig. 10. Cost-GHG multi-objective pareto fronts for all semi-detached buildings. L and T abbreviate retrofit to limit and target U-Values.

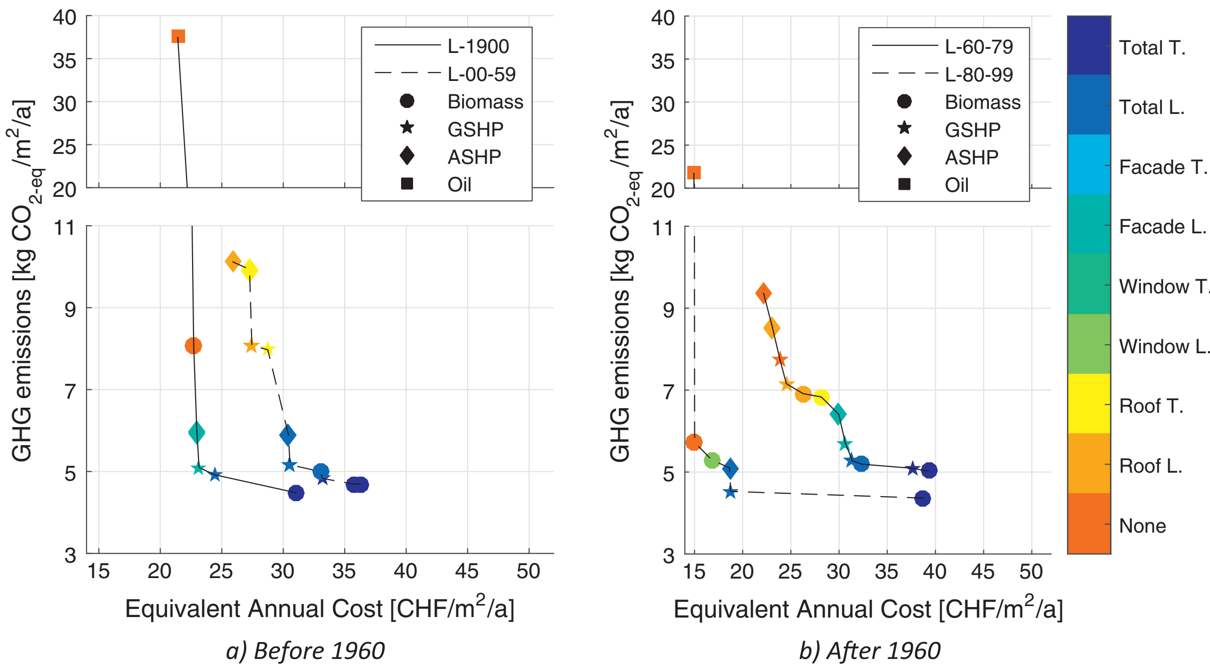

Fig. 11. Cost-GHG multi-objective pareto fronts of all large buildings. L and T abbreviate retrofit to limit and target U-Values.

Table 7
Proposed strategy for the entire community.

Category	Heating system	Retrofit level	Costs [CHF/m^2/a]	GHG [kg $CO_{2\text{-eq}}$/m^2/a]
D-1900	GSHP/GSHP	Roof L/Total L	26.9/23.2	7.42/3.98
SD-1900	GSHP/Bio	Roof L/Roof L	27.8/25.3	7.33/6.92
L-1900	GSHP/Bio	Roof L/None	27.3/22.7	8.15/8.06
D-00-59	GSHP/ GSHP	Roof L/Total L	30/23.8	8.32/4.98
L-00-59	GSHP/GSHP	Roof L/Total L	27.4/23.3	8.08/5.9
D-60-79	GSHP/GSHP	Roof L/Façade L	29.6/29.5	9.09/6.8
SD-60-79	GSHP/GSHP	Façade L/Façade L	30.9/23.8	4/4
L-60-79	GSHP/GSHP	Roof L/Total L	24.5/24.3	7.16/5.29
D-80-99	GSHP/GSHP	Total L/Total L	28.6/21.5	6.45/6.45
SD-80-99	GSHP/GSHP	Roof T/Total L	23.4/25.2	4.38/3.25
-80-99	ASHP/GSHP	Total L/Total L	25.7/18.7	5.1/4.53

We have found that for oil heated buildings, a continued use of oil causes very high environmental impacts of 20–40 kg $CO_{2\text{-eq}}$/m^2/a. Switching fuels from oil to biomass reduces GHG emissions by up to 80% at a maximum cost increase of 6% compared to oil. Biomass heating is preferred for low retrofit from none to window target scenarios. As the allowable GHG emissions decrease, the cost barrier to replace the high temperature heat distribution system is overcome, and the same ranking of heating systems from ASHP to GSHP to biomass is observed for façade to whole building retrofit.

4.3.2. Retrofit

While the retrofit level typically increases from no retrofit to whole building SIA380/1 target retrofit as GHG emissions decrease, the optimisation sometimes trades roof or window insulation for a less GHG intensive heating system, as both options are similarly effective at reducing GHG emissions at low costs. The pareto front of building D-1900, depicted in Fig. 9a is such an example, switching between roof and window retrofit, ASHP and GSHP as GHG emissions decrease.

When comparing semi-detached and large buildings across the ages, the pareto fronts' distance to the origin increases with building age until 1900, as expected due to the increased costs to retrofit older buildings. As the buildings from 1900 to 59 have the worst initial insulation levels, their pareto curve is expected to be the furthest from the origin. However, Fig. 4 shows that D-60-79 and D-80-99 have a significantly higher lighting electricity demand compared to the other buildings, which reduces their potential to reach low GHG emissions, leading to a best environmental performance between 6 and 7 kg $CO_{2\text{-eq}}$/m^2 for both buildings.

4.4. Strategies for the entire community

Although building owners usually make retrofit decisions individually, strategies for the entire community can and should be explored to determine their implications for that community. The multi-objective optimisation is repeated for every unique heating system in a typical building, where oil boilers are replaced by electrical resistance heaters and vice versa. In Table 7, the first entries for the heating system, retrofit level, cost and GHG factor are applied to buildings that are originally heated with electricity; the second set of entries are the optimal values selected for oil-heated buildings.

Although biomass as an energy carrier yields the best environmental performance, it was not chosen since it is a limited resource in densely populated areas and countries such as Switzerland,

Table A1
Building simulation input parameters from the building stock survey. The number of floors is given as Number of floors above ground level + basement.

Building identifier	D-1900	SD-1900	L-1900	D-00-59	L-00-59	D-60-79	SD-60-79	L-60-79	D-80-99	SD-80-99	L-80-99
Total Floor area [m^2]	822	614	875	700	675	370	823	1019	610	574	1315
Occupied Floor area [m^2]	483	400	552	523	509	291	498	766	473	411	866
Building footprint [m^2]	190	160	215	192	180	108	180	276	172	150	308
Façade area [m^2]	452	468	495	420	405	235	388	469	286	368	605
Window to wall ratio [%]	12	18	15	15	15	14	16	20	15	20	9
Number of floors [–]	3 + 1	3 + 1	3 + 1	2.5[a] + 1	2.5 + 1	2 + 1	3 + 1	2.5 + 1	2 + 1	3 + 0	3 + 1
Building height [m]	8	9	8.3	7.5	6	5.6	7.2	5	5.6	5	8.4
Number of inhabitants [–]	2	4	9	1	5	3	7	4	2	2	7
Roof slope [°]	40	10	10	40	30	20	30	25	20	40	10
Roof Area for solar [m^2]	128	100	110	130	110	60	108	130	84	97	207
Roof type	Gabled	Hipped	Gabled								
Historical Protection	Yes					No		Yes	No		

[a] 2 Regular floors plus inhabited roof space.

Table A2
Assumed wall, roof and window constructions. Thicknesses are given in metres, the outermost layer is at the top, the innermost at the bottom.

Component	Before 1900		1900–1959		1960–1979		1980–1999	
Walls	Plaster	0.03	Brickwork	0.2	Brickwork	0.1	Brickwork	0.1
	Quarrystones	0.5	Gypsum	0.013	Air gap	0.01	Mineral Wool	0.05
	Gypsum	0.02			Concrete	0.1	Concrete	0.1
					Gypsum	0.013	Gypsum	0.015
Roof	Clay Tiles	0.025	Clay Tiles	0.025	Clay Tiles	0.025	Clay Tiles	0.025
	Wood battons	0.14	Wood Battons	0.08	Mineral Wool	0.05	Mineral Wool	0.15
					Roofing Felt	0.005	Roofing Felt	0.005
Floor	Quarrystones	0.2	Quarrystones	0.3	Concrete	0.1	Concrete	0.1
	Timber Flooring	0.05	Timber Flooring	0.06	Floor Screed	0.07	Floor Screed	0.07
					Timber Flooring	0.03	Timber Flooring	0.03

Table A3
Additional insulation thicknesses [m] and costs [CHF/m^2] for each retrofit intervention. EPS is expanded polystyrene, MW mineral wool and PUR polyurethane.

Component	Before 1900		1900–1959		1960–1979		1980–1999	
	Thickness	Costs	Thickness	Costs	Thickness	Costs	Thickness	Costs
Walls limit (EPS)	0.06 (PUR)	165	0.08 (PUR)	170	0.1	265	0.12	280
Walls target (EPS)	0.10 (PUR)	175	0.12 (PUR)	180	0.2	400	0.2	400
Roof limit (MW)	0.10	145	0.12	150	0.12	150	0	0
Roof target (MW)	0.22	240	0.22	240	0.26	280	0.26	280
Floor limit (EPS)	0.1	105	0.08	100	0.1	105	0	0
Floor target (EPS)	0.15	135	0.14	130	0.15	135	0.16	140
Windows limit	–	900						
Windows target	–	1100						

especially as long transportation distances increase GHG emissions. When considering all buildings in the presented case study, a possible policy to minimise both costs and GHG emissions could be to encourage owners of older, protected buildings to combine partial retrofit with a heat pump or biomass heating systems, and to retrofit the envelope of newer buildings completely, combined with heat pump systems. Although façade and whole building retrofit are a possible solution for protected buildings at a high cost level, inside insulation might not be feasible for a significant share of buildings due to hygrothermal reasons. Therefore, the strategy summarised in Table 7 is chosen as an example solution which could be applied to all buildings.

Such a solution would result in total annual GHG emissions of 504 t $CO_{2\text{-eq}}$/year at a cumulated total cost of 1.91 million CHF/year for 214 buildings. Compared to the current, not optimised situation, the GHG emissions of the entire village are reduced by 76% at a cost increase of 3%. The area-specific GHG emissions of 6.5 kg $CO_{2\text{-eq}}$/year/m^2 are below the 2000 W society recommendation of 10 kg $CO_{2\text{-eq}}$/year/m^2 for retrofit and building use in existing buildings, but the comparison cannot be done directly as slightly different GHG factors are used for the 2000 W society.

5. Conclusions

In this paper, a method for a multi-objective optimisation of building energy systems and retrofit is presented, and applied to a selection of typical residential buildings in Zernez, demonstrating the trade-offs between costs and GHG emissions, building system and retrofit measures. It is found that the Minergie-P heating energy standard could be reached for most buildings with sufficient insulation. However, high retrofit costs and historical protection can make a combination of partial retrofit and a change in building systems more attractive for certain building categories. The set of pareto-optimal transformation strategies are found to depend on the original heating system, while age and size of the building influence the achievable GHG emissions and related costs.

In oil-heated buildings, a change to biomass-based heating systems decreases GHG emissions significantly at low extra costs, as the heat distribution system does not have to be replaced. Although oil heating is the cheapest solution for larger energy demands, the very high GHG emissions make oil heating systems unacceptable when environmental limits have to be respected.

Without the additional costs for changing the heat distribution system, air- and ground source heat pumps are financially attractive compared to biomass system, forcing their inclusion in electrically heated buildings where a central heat distribution system has to be installed irrespective of retrofit, and in buildings with high retrofit levels and significantly reduced heating demand.

Retrofit, though highly attractive for GHG emissions, has a high impact on costs and should be coordinated with a change in heating systems to achieve optimal results.

From the multi-objective optimisation, a suitable transformation strategy can be deduced for a given set of preferences between costs and GHG emissions. While the principle is demonstrated with a manually selected set of options in this study, more refined mechanisms such as an optimisation which chooses a strategy for each building to reach a certain GHG emission limit at minimum costs, or at equal costs for all building owners are part of ongoing research.

When balancing retrofit and building systems, other factors such as thermal comfort, hygrothermal performance, draft risk and acoustics can be important for building owners and users which might be useful to consider in the future. A further option for future work would be to compare this study's scenarios to the replacement certain buildings, with possible gains in building value, comfort, energy performance and land use.

The building level results of this study can provide guidance to individual building owners and investors, showing different transformation options. For community and regional policy makers and planners, suitable strategies at community level can be identified and incentivised, based on the available transformation options and potential budget, historical protection, or resource availability constraints.

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Appendix A. Typical building parameters

Table A1 contains the relevant survey data for each typical building, while Table A2 summarises the assumed wall, roof and floor constructions per age category. Double Clear 6/13 mm Air windows are assumed to be currently used in all buildings, replaceable by Triple Low Emissivity Clear 3/6 mm Air windows to reach SIA 380/1 limit values, and Quadruple Low Emissivity 3 mm/8 mm Krypton windows for SIA 380/1 target values.

Table A3 lists the additional insulation thicknesses and costs for retrofit.

References

[1] Levermore G. A review of the IPCC Assessment Report Four, Part 1: the IPCC process and greenhouse gas emission trends from buildings worldwide. Build Serv Eng Res Technol 2008;29:349–61. http://dx.doi.org/10.1177/0143624408096263.

[2] Ó Broin E, Nässén J, Johnsson F. Energy efficiency policies for space heating in EU countries: a panel data analysis for the period 1990–2010. Appl Energy 2015;150:211–23. http://dx.doi.org/10.1016/j.apenergy.2015.03.063.

[3] Swiss Federal Office of Energy. Energiestrategie 2050 [WWW Document]. Energiestrategie 2050; 2016. <http://www.bfe.admin.ch/energiestrategie2050/index.html?lang=de> [accessed 6.23.16].

[4] Blindenbacher T, Herbst N. 2000-Watt-Gesellschaft [WWW Document]. 2000-Watt-Ges; 2016. <http://www.2000watt.ch/> [accessed 6.23.16].

[5] Lehni J, Lerch S, Müller C. Minergie [WWW Document]. Minergie; 2016. <http://www.minergie.ch/> [accessed 6.23.16].

[6] Hong T, Koo C, Kim J, Lee M, Jeong K. A review on sustainable construction management strategies for monitoring, diagnosing, and retrofitting the building's dynamic energy performance: focused on the operation and maintenance phase. Appl Energy 2015;155:671–707. http://dx.doi.org/10.1016/j.apenergy.2015.06.043.

[7] Ma Z, Cooper P, Daly D, Ledo L. Existing building retrofits: methodology and state-of-the-art. Energy Build 2012;55:889–902. http://dx.doi.org/10.1016/j.enbuild.2012.08.018. Cool Roofs, Cool Pavements, Cool Cities, and Cool World.

[8] Nagy Z, Rossi D, Hersberger C, Irigoyen SD, Miller C, Schlueter A. Balancing envelope and heating system parameters for zero emissions retrofit using building sensor data. Appl Energy 2014;131:56–66. http://dx.doi.org/10.1016/j.apenergy.2014.06.024.

[9] Evins R. A review of computational optimisation methods applied to sustainable building design. Renew Sustain Energy Rev 2013;22:230–45. http://dx.doi.org/10.1016/j.rser.2013.02.004.

[10] Machairas V, Tsangrassoulis A, Axarli K. Algorithms for optimization of building design: a review. Renew Sustain Energy Rev 2014;31:101–12. http://dx.doi.org/10.1016/j.rser.2013.11.036.

[11] Schwartz Y, Raslan R, Mumovic D. Implementing multi objective genetic algorithm for life cycle carbon footprint and life cycle cost minimisation: a building refurbishment case study. Energy 2016;97:58–68. http://dx.doi.org/10.1016/j.energy.2015.11.056.

[12] Chantrelle FP, Lahmidi H, Keilholz W, Mankibi ME, Michel P. Development of a multicriteria tool for optimizing the renovation of buildings. Appl Energy 2011;88:1386–94. http://dx.doi.org/10.1016/j.apenergy.2010.10.002.

[13] Ascione F, Bianco N, De Stasio C, Mauro GM, Vanoli GP. A new methodology for cost-optimal analysis by means of the multi-objective optimization of building energy performance. Energy Build 2015;88:78–90. http://dx.doi.org/10.1016/j.enbuild.2014.11.058.

[14] Penna P, Prada A, Cappelletti F, Gasparella A. Multi-objectives optimization of energy efficiency measures in existing buildings. Energy Build 2015;95:57–69. http://dx.doi.org/10.1016/j.enbuild.2014.11.003. Special Issue: Historic, historical and existing buildings: designing the retrofit. An overview from energy performances to indoor air quality.

[15] Ascione F, Bianco N, De Stasio C, Mauro GM, Vanoli GP. Multi-stage and multi-objective optimization for energy retrofitting a developed hospital reference building: a new approach to assess cost-optimality. Appl Energy 2016;174:37–68. http://dx.doi.org/10.1016/j.apenergy.2016.04.078.

[16] Shao Y, Geyer P, Lang W. Integrating requirement analysis and multi-objective optimization for office building energy retrofit strategies. Energy Build 2014;82:356–68. http://dx.doi.org/10.1016/j.enbuild.2014.07.030.

[17] Hamdy M, Hasan A, Siren K. A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010. Energy Build 2013;56:189–203. http://dx.doi.org/10.1016/j.enbuild.2012.08.023.

[18] Asadi E, da Silva MG, Antunes CH, Dias L. State of the art on retrofit strategies selection using multi-objective optimization and genetic algorithms. In: Torgal FP, Mistretta M, Kaklauskas A, Granqvist CG, Cabeza LF, editors. Nearly zero energy building refurbishment. London: Springer; 2013. p. 279–97.

[19] Diakaki C, Grigoroudis E, Kolokotsa D. Performance study of a multi-objective mathematical programming modelling approach for energy decision-making in buildings. Energy 2013;59:534–42. http://dx.doi.org/10.1016/j.energy.2013.07.034.

[20] Stadler M, Groissböck M, Cardoso G, Marnay C. Optimizing distributed energy resources and building retrofits with the strategic DER-CA model. Appl Energy 2014;132:557–67. http://dx.doi.org/10.1016/j.apenergy.2014.07.041.

[21] Karmellos M, Kiprakis A, Mavrotas G. A multi-objective approach for optimal prioritization of energy efficiency measures in buildings: model, software and case studies. Appl Energy 2015;139:131–50. http://dx.doi.org/10.1016/j.apenergy.2014.11.023.

[22] Haimes YY, Ladson LS, Wismer DA. Bicriterion formulation of problems of integrated system identification and system optimization. 345 E 47th st, New York, NY 10017-2394: IEEE-INST Electrical Electronics Engineers Inc; 1971.

[23] Antipova E, Boer D, Guillén-Gosálbez G, Cabeza LF, Jiménez L. Multi-objective optimization coupled with life cycle assessment for retrofitting buildings. Energy Build 2014;82:92–9. http://dx.doi.org/10.1016/j.enbuild.2014.07.001.

[24] Bayraktar M, Fabrizio E, Perino M. The extended building energy hub: a new method for the simultaneous optimization of energy demand and energy supply in buildings. HVAC R Res 2012;18:67–87. http://dx.doi.org/10.1080/10789669.2011.588300.

[25] Schütz T, Schiffer L, Harb H, Fuchs M, Müller D. Optimal design of energy conversion units and envelopes for residential building retrofits using a comprehensive MILP model. Appl Energy 2017;185(Part 1):1–15. http://dx.doi.org/10.1016/j.apenergy.2016.10.049.

[26] Jennings M, Fisk D, Shah N. Modelling and optimization of retrofitting residential energy systems at the urban scale. Energy 2014;64:220–33. http://dx.doi.org/10.1016/j.energy.2013.10.076.

[27] Mauro GM, Hamdy M, Vanoli GP, Bianco N, Hensen JLM. A new methodology for investigating the cost-optimality of energy retrofitting a building category. Energy Build 2015;107:456–78. http://dx.doi.org/10.1016/j.enbuild.2015.08.044.

[28] Keirstead J, Jennings M, Sivakumar A. A review of urban energy system models: approaches, challenges and opportunities. Renew Sustain Energy Rev 2012;16:3847–66. http://dx.doi.org/10.1016/j.rser.2012.02.047.

[29] Tindale A, Potter S. DesignBuilder. DesignBuilder Software Ltd; 2014.

[30] U.S. Department of Energy. EnergyPlus energy simulation software. U.S. Department of Energy; 2013.
[31] Schweizerischer Ingenieur- und Architektenverein. Standard-Nutzungsbedingungen für Energie- und Gebäudetechnik (Norm No. 2024). Zürich: SIA; 2006.
[32] Jordan U, Vajen K. DHWCalc. Kassel: University of Kassel; 2003.
[33] Geidl M, Koeppel G, Favre-Perrod P, Klockl B, Andersson G, Frohlich K. Energy hubs for the future. IEEE Power Energy Mag 2007;5:24.
[34] Allegrini J, Orehounig K, Mavromatidis G, Ruesch F, Dorer V, Evins R. A review of modelling approaches and tools for the simulation of district-scale energy systems. Renew Sustain Energy Rev 2015;52:1391–404. http://dx.doi.org/10.1016/j.rser.2015.07.123.
[35] Mavromatidis G, Evins R, Orehounig K, Dorer V, Carmeliet J. Multi-objective optimization to simultaneously address energy hub layout, sizing and scheduling using a linear formulation. In: Engineering optimization IV. Presented at the international conference on engineering optimization. Lisbon: CRC Press/Balkema; 2014. p. 609–14.
[36] Roelofs M, Bisschop J. AIMMS. AIMMS B.V; 2015.
[37] IBM Corporation. IBM ILOG CPLEX. IBM; 2014.
[38] Zhou Z, Liu P, Li Z, Pistikopoulos EN, Georgiadis MC. Impacts of equipment off-design characteristics on the optimal design and operation of combined cooling, heating and power systems. Comput Chem Eng 2013;48:40–7. http://dx.doi.org/10.1016/j.compchemeng.2012.08.007.
[39] Fish JCL. Engineering economics: first principles. New York: McGraw-Hill; 1915.
[40] Orehounig K, Evins R, Dorer V. Integration of decentralized energy systems in neighbourhoods using the energy hub approach. Appl Energy 2015;154:277–89. http://dx.doi.org/10.1016/j.apenergy.2015.04.114.
[41] Orehounig K, Mavromatidis G, Evins R, Dorer V, Carmeliet J. Towards an energy sustainable community: an energy system analysis for a village in Switzerland. Energy Build 2014;84:277–86. http://dx.doi.org/10.1016/j.enbuild.2014.08.012.
[42] Village of Zernez. Zernez Energia 2020 [WWW Document]; 2011. <http://zernezenergia2020.ch/home/> [accessed 6.23.16].
[43] Orehounig K, Mavromatidis G, Evins R, Dorer V, Carmeliet J. Predicting energy consumption of a neighbourhood using calibrated building performance simulations. In: Proceeding of Building Simulation and Optimization (BSO 2014). Presented at the Building Simulation and Optimization, BSO 2014. IBPSA; 2014. p. 72.
[44] Swiss Federal Office of Topography. Karten der Schweiz; 2016.
[45] Brunner CU, Nänni J. Wärmebrückenkatalog – 3. Altbaudetails. Zürich: SIA; 1993.
[46] Schweizerischer Ingenieur- und Architektenverein. Thermische Energie im Hochbau (Norm No. 380/1). Zürich: SIA; 2010.
[47] Schweizerischer Ingenieur- und Architektenverein. Wärmeschutz, Feuchteschutz und Raumklima in Gebäuden (Norm No. 180). Zürich: SIA; 2014.
[48] MeteoSwiss. Monatswerte 2011–2015 der Station Scuol SCU; 2016.
[49] EnDK - Konferenz Kantonaler Energiedirektoren. GEAK | Gebäudeenergieausweis der Kantone [WWW Document]; 2015. <https://www.geak.ch/> [accessed 6.23.16].
[50] Amt für Energie und Verkehr Graubünden. Beitragsgesuche für einen Gesamtsanierungsbonus und für haustechnische Anlagen in bestehenden Bauten - Leitfaden und Bedingungen für Beitragsgesuche. Chur: AEV Graubünden; 2014.
[51] Swiss Federal Office of Energy. Einmalvergütung und Eigenverbrauch für kleine Photovoltaik-Anlagen (Fact Sheet). Ittigen: Swiss Federal Office of Energy; 2014.
[52] Weidema BP, Bauer C, Hischier R, Mutel C, Reinhard J, Vadenbo CO, et al. The ecoinvent database: overview and methodology, Data quality guideline for the ecoinvent database version 3; 2013.
[53] Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren. Ökobilanzdaten im Baubereich; 2014.