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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…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