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OPTIMAL ENERGY SYSTEM TRANSFORMATION OF A NEIGHBOURHOOD

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Abstract

This paper presents a methodology for optimising the energy system transformation of a neighbourhood that can simultaneously assess energy supply and retrofitting measures. The method combines the assessment of retrofitting measures using dynamical simulation tools and multi-criteria decision making based on the energy hub concept. Considered objectives include minimisation of life cycle costs, CO_2 emissions, primary energy use and a weighted environmental impact measure defined according to the current Swiss environmental policy.

In this study, typical buildings of various ages, sizes and retrofit states are considered, which allows both individual building owners and neighbourhood or town policy makers to find a retrofit strategy tailored to their individual or collective criteria and goals.

The approach is then applied to a number of typical residential buildings in the Swiss village of Zernez, which has a diverse residential building stock in terms of age, size, and retrofit states amongst other constraints.

The performance of various retrofitting options of the building envelope and system changes including biomass heating systems, heat pumps, photovoltaic, and solar thermal panels are assessed. Simulation results show a diverse choice, mainly depending on building age and optimisation criteria. Individual strategies for different age groups are therefore proposed to reach the goals of the Swiss energy strategy 2050 and a 2000 Watt society.

Keywords:

Retrofit and Building System Optimisation; Energy Hub; CO_2 Reduction; Neighbourhood

1 INTRODUCTION

When facing future energy and environmental challenges, buildings have a large impact as major energy consumers with long life cycles [1].

With the vast number of possible solutions, a systematic approach is needed to determine economic and environmental viabilities for each transformation strategy.

This paper presents a methodology for optimising building energy system transformations that can assess energy supply and retrofitting measures simultaneously, combining the assessment of retrofitting measures using dynamical simulation tools and multi-criteria decision making based on the energy hub concept.

Similar studies focusing on multi-objective optimisation of energy demand and supply measures were conducted by Bayraktar et. al [2]. Tadeu et. al. [3] and Schwartz et. al [4] add a life cycle perspective while focusing on retrofit measures. Within the present contribution, considered objectives include minimisation of costs, CO_2 emissions, primary energy (PE) use and a weighted environmental impact measure defined according to the current Swiss environmental policy (UBP13 [5]).

The approach is applied to typical residential buildings in the Swiss village of Zernez, which is currently running a pilot project to reduce its use of fossil fuels and environmental impact.

2 METHODS

First, the energy demands of each building are simulated for various retrofit scenarios. The resulting demand profiles serve as inputs for an energy hub optimisation, which optimises energy supply systems for every building and retrofit scenario.

2.1 Building energy demand and supply simulations

Using geometrical data and information about the location, age and construction type, buildings are modelled and simulated in EnergyPlus [6]. Domestic hot water (DHW) demands are simulated with DHWcalc [7].

8760 hourly values for heat, DHW and electricity demands are simulated for every building and retrofit scenario, and serve as inputs for the energy hub optimisation. Furthermore, the irradiation on south facing roof areas is determined to get the available solar energy.

2.2 Energy hub optimisation

Energy supply systems to provide electricity, space heating and DHW are optimised using an energy hub, formulated according to the method of Mavromatidis et al. [8]. The following types of constraints are implemented using AIMMS [9]:

- Energy balances for heat, electricity and DHW storage
- Non-violation constraints on the maximum power of each conversion system, used to determine its capacity
- Constraints imposing fixed costs and minimum plant capacities if a technology is chosen
- Maximum charge and discharge rates of the storage tank
- A constraint preventing simultaneous grid electricity consumption and feed in

This study's energy hub is shown in Fig. ***1***, with inputs I and outputs L. Typical residential energy conversion and storage systems are considered: Air (ASHP) and ground source heat pumps (GSHP), biomass boilers, photovoltaic (PV) and solar thermal (ST) panels. A DHW tank is assumed to be present in all buildings, sized according to the number of inhabitants.

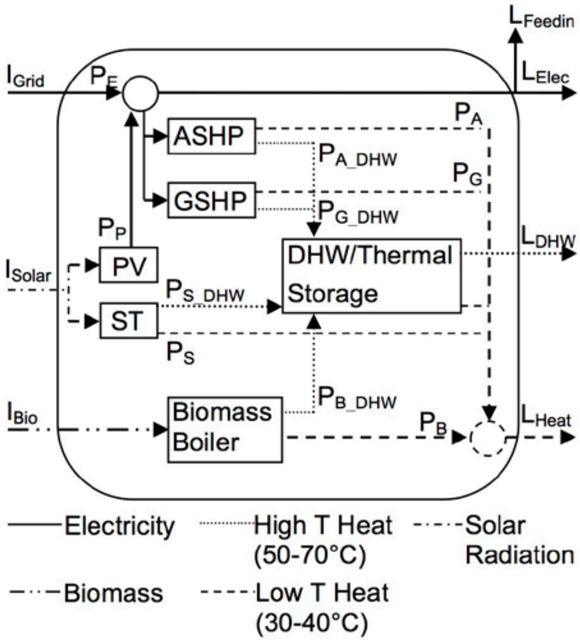

Fig. 1: Energy hub layout.

Two types of objective functions are considered, annualised costs and life cycle environmental impacts.

Each energy conversion technology T contributes to the costs with its investment cost, split into fixed cost (fc) and subsidies (fs), and capacity (cap) dependent linear costs (lc) and subsidies (ls). The binary decision variables y_T determine whether a technology is installed. The input energy carriers ($\boldsymbol{i}$) are multiplied with their costs ($\mathbf{c}$), the feedin electricity (l_{feedin}) with the feedin tariff (c_{feedin}) and summed over time. The resulting objective function for costs o_1 is:

$$\boldsymbol{o_1} = \sum_{\mathrm{T}}([\mathbf{fc_T} - \mathbf{fs_T}] * \boldsymbol{y_T} + [\mathbf{lc_T} - \mathbf{ls_T}] * \boldsymbol{cap_T}) / \mathbf{a_T} + \sum_{\mathrm{t}}(\boldsymbol{i} * \mathbf{c} - \boldsymbol{l_{feedin}} * \mathbf{c_{feedin}}) + \mathbf{c_R}/\mathbf{a_R} \qquad (1)$$

$$\boldsymbol{i} = [\boldsymbol{i_{Grid}} \quad \boldsymbol{i_{Bio}}], \quad \mathbf{c} = [\mathbf{c_{Grid}} \quad \mathbf{c_{Bio}}]^{\mathbf{T}} \qquad (2)$$

Investment and retrofit ($\mathrm{c_R}$) costs are annualised using the equivalent annual cost method [10], considering their lifetimes τ and a yearly interest rate r.

The nonfinancial objective functions can be expressed as the products of all conversion outputs ($\boldsymbol{p}$, indicated as P_i in Fig. ***1***) with their impact factors $\mathbf{f_E}$ summed over time, and the impact of all retrofit materials R with their masses ($\mathrm{m_R}$), impact factors ($\mathrm{f_R}$) and lifetimes (τ_R):

$$\boldsymbol{o_2} = \sum_{\mathrm{t}}(\boldsymbol{p} * \mathbf{f_E}) + \sum_{\mathrm{R}}(\mathbf{m_R} * \mathbf{f_R})/\boldsymbol{\tau_R} \qquad (3)$$

3 THE CASE STUDY

The presented method is applied to residential buildings in Zernez, for which building database in terms of geometry, energy use and retrofit state was compiled in 2012. 214 residential buildings are categorised in terms of their age,

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size and current heating system. 11 typical buildings, ranging from detached (D) to semi-detached (SD) and large multifamily houses (L), built between 1870 and 1999 are selected to represent the different categories.

3.1 Modelling input data

Geometrical data comes from the Zernez database and a 1:25000 map [11]. Wall, roof and floor constructions and U-values are taken from an overview of historical constructions [12], whereas internal gains, daily DHW volumes, heating setpoints, lighting and occupancy profiles are calculated using the SIA 2024 standard [13], assuming a floor area distribution of 80% living space, 10% kitchen and 10% bathrooms for all buildings.

In addition to the base case without retrofit, 8 scenarios are analysed. The following envelope components are retrofitted either to the SIA 380/1 [14] limit or target values:

- Roof
- Windows
- Façade (windows and walls)
- Whole building

For buildings built after 1960, the U-Values are adjusted by adding a typical insulation material such as expanded polystyrene on the outside.

An aerogel is applied to older, protected buildings. Air change assumptions are given in Table 2.

Energy demand simulations are based on 2002 weather data from the neighbouring village of Scuol.

For the energy hub optimisation, life cycle costs, CO_2 [15], (nonrenewable) Primary Energy and UBP13 serve as objective functions.

Unsubsidised costs, minimum plant size and system lifetime assumptions are based on commercially available systems in Switzerland. DHW tanks are assumed to have a capacity of 600-1000 l, depending on the number of inhabitants. In Table 3, the assumed energy carrier costs are listed, while Table 1 summarises the assumed parameters for all energy conversion systems, including the current oil and electric resistance heating systems, which are used as a reference.

Retrofit costs are taken from a Swiss building energy and retrofit analysis tool [16], and discounted over a lifetime of 50 years.

Federal [17] and Cantonal [18] subsidies for retrofit and energy systems are included in the subsidised cost optimisation. All investment costs are annualised using a yearly discount rate of 5%.

Life cycle CO_2, PE and UBP13 are calculated per unit of final delivered energy. For building retrofit, the CO_2, PE and UBP13 embedded in the materials are considered [5] and divided by the lifetime of 50 years.

Retrofit State/Age	ACR [1/h]
Base case (<1980)	0.7
Base case (>1980)	0.6
Roof	0.6
Windows	0.6
Façade	0.5
Whole Building (SIA380/1 Limit)	0.4
Whole Building (SIA380/1 Target)	0.3

Table 2: Assumed air change rates (ACR).

	Cost [CHF/kWh]
Electricity	0.2
Electricity (feedin)	-0.15
Wood (logs)	0.075
Wood (pellets)	0.09
Heating Oil	0.1

Table 3: Assumed electricity and fuel costs.

Technology	Fixed Cost [CHF]	Linear Cost [CHF/kW]	Lifetime [years]	Minimum size [kW]	Efficiency / COP
Biomass boiler	32'000	100	20	20	0.7
GSHP	20'000	2'380	20[1]	5	4, 2.75[2]
ASHP	18'300	1'020	20	5	3, 2[2]
ST	4'000	1'000 [CHF/m^2]	25	4 [m^2]	0.7
PV	900[3]	400 [CHF/m^2]	30	5 [m^2]	0.15
Electrical heating	14'600	730	30	-	1
Oil boiler	16'600	460	25	-	0.85

[1] The GSHP borehole, which is assumed to make up 45% of the entire system cost, is discounted over 50 years.
[2] Heat pumps are assumed to have a higher COP for heating than for DHW
[3] For protected buildings, built-in PV modules with fixed costs of 3'000 CHF are considered.

Table 1: Summary of energy conversion parameters.

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4 RESULTS AND DISCUSSION

4.1 Energy demands

Figure 2 shows the simulated heating demands, which are reduced by more than 50% from the base case to maximum retrofit in all buildings.

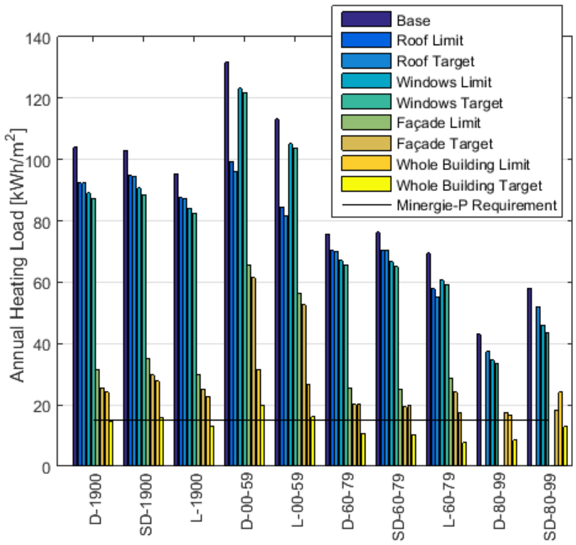

Fig. 2: Simulated heating demands of all buildings in all retrofit states.

U-values, and air change rates, which primarily depend on user behaviour and building airtightness, have the largest influence on heating demands. A sensitivity analysis for an old building (D-1900) shows that changing each parameter by 10% leads to a 5% change in heating demand.

The simulated average annual electricity consumption of 34.6 kWh/m^2 is higher than in the survey, but still at the lower bound of SIA 2024.

4.2 Costs

Subsequently, the energy demands for all buildings and scenarios are used as inputs for the energy hub calculations. Figure 3 shows optimisation results in terms of average equivalent annual cost breakdowns per age category for the different scenarios, including the original heating system solutions. Costs are divided into operational costs (Energy), costs for building envelope interventions (Retrofit), costs for system interventions (System Investment), and additional total costs if subsidies are not considered (Unsubsidised). Cases "Original Heating System" and "Base" have the same energy demand, but in the Base case, the energy system is optimised.

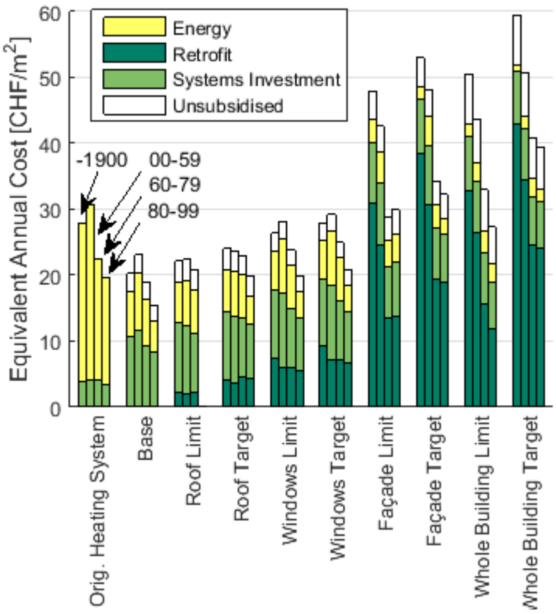

Fig. 3: Age-averaged total costs.

The results suggest that ASHP, PV and no retrofit are the cheapest unsubsidised solution for all buildings. As retrofit, efficient heating systems and PV are all subsidised in Graubünden as of May 2015, the subsidised cost structure is still dominated by the retrofit costs. As subsidies are doubled once the whole building is retrofitted, a whole building limit retrofit becomes cheaper than a façade retrofit to SIA target values.

Retrofitting old, protected buildings with aerogel costs up to 120% more than the current state, where the cost spread between the current configuration and a whole building, SIA limit retrofit decreases to 5-60% for buildings in the 1960-79 category and to 0-30% for buildings built in 1980-99.

4.3 Life cycle CO_2

Figure 4 shows CO_2 optimisation results and the current state per age category. As local wood logs are a limited resource, three scenarios are evaluated:

When minimising CO_2 without biomass restrictions, maximum PV and wood log heating systems are preferred.

If biomass is available as wood pellets, pellet heating systems are combined with PV and – for some buildings – small solar thermal plants.

If biomass is unavailable, GSHP are used in conjunction with PV and in some cases small solar thermal systems.

Total CO_2 emissions are dominated by the energy use, which leads to a decrease in total CO_2 emissions with increasing retrofit. The minimum occurs between façade and whole building retrofit.

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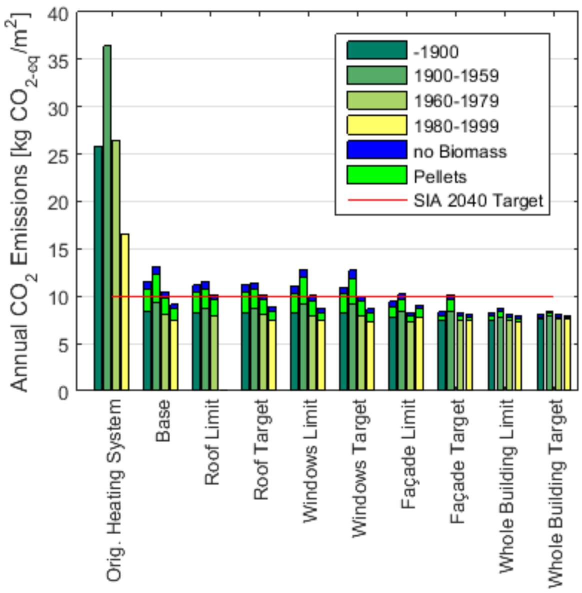

Fig. 4: Age-averaged total CO_2 emissions.

4.4 Primary Energy and UBP13

Nonrenewable PE, as shown in Fig. ***5***, is minimised with GSHP and maximum PV.

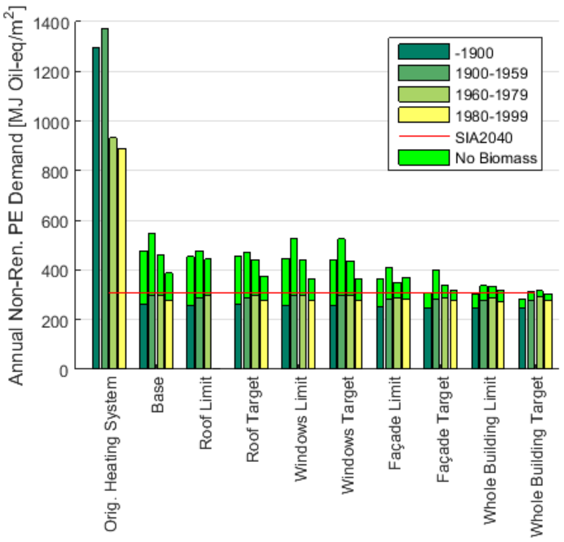

Fig. 5: Nonrenewable PE consumption.

The non-renewable PE and UBP13 optimisations leads to similar energy system choices as in the CO_2 scenarios. Biomass is combined with maximised PV, or GSHP with PV and small solar thermal plants if biomass is not available. Maximum retrofit is preferred for all buildings.

4.5 Summary

An overview of the preferred systems and retrofit states for all objectives is given in Table 4. With the exception of GSHP and ASHP for cost, the technology choice is independent of the building age, size and type.

Objective	Heating	Solar	Retrofit
Cost	A/GSHP	PV	None
CO_2, UBP13 and non-ren. PE	Biomass (Logs)	PV	Façade/ Whole Building
CO_2 – no Logs	Biomass (Pellets)	PV + ST	Whole Building
CO_2, UBP13 and non-ren. PE – no Bio	GSHP	PV + ST	Whole Building
PE	GSHP	PV	Whole B.

Table 4: Overview of preferred technologies and retrofit states.

Retrofitting buildings built after 1960 to SIA 380/1 target values would lead to an average cost increase of 20% compared to the current configuration, and would substantially improve the ecological performance, with most buildings complying with the 2000W society goals [19].

Building age was found to have a larger influence than size on all objectives. Due to their increased compactness, larger buildings perform slightly better than single family homes when comparing all objectives per m^2 of inhabited floor area.

5 CONCLUSION

This study presents a method to assess and optimise retrofit and energy supply systems simultaneously, which is applied to typical residential buildings in Zernez, Switzerland.

All considered technologies are favoured for at least one objective function, whereby a combination of fully retrofitted building envelope together with a biomass or heat pump based system leads to lowest environmental impact.

However, optimisation results for costs show that retrofitting is an expensive solution, especially for protected buildings. Most cantons subsidise retrofit, although for older buildings, partial retrofitting together with a local biomass based heating system might be a more optimal way to achieve environmental targets. Without retrofit, 2000W targets are not reached for all buildings. However, retrofit typically leads to improved comfort, which is not considered here, and which might bring additional value for the buildings.

To conclude, the present contribution shows that the optimal envelope and system interventions for residential buildings is strongly dependent on the objective, and focusing only on a single parameter might not always lead to the optimal choices.

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