A method to support multi-criteria decision making for building systems update at urban scale

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Abstract

This paper presents a workflow to support the decision making for identifying building energy efficiency measures for multiple buildings in a neighborhood. The workflow consists of a method to extract geo-spatial information, compute renewable potentials and energy demands and an optimization model to evaluate the most suitable retrofitting scenario in terms of envelope and system update based on multi-criteria decission making. The developed method is applied on a case study pertaining to an existing rural area. Modelling results include best performing options in terms of CO_2 emissions while minimizing the resulting costs of the possible energy system solutions are derived.

Introduction

Buildings and urban energy systems are confronted with energy and greenhouse gas emission challenges in order to meet future energy strategy targets. This typically requires a combination of measures including updating current heating systems, integrating renewable energy sources, and retrofitting the existing building envelopes. Therefore, tools that allow for multi-criteria assessments of a combination of measures are required to support this decision-making process.

Usually building owners have to retain an energy consultant to identify the most environmentally and economically optimal intervention for their building.

This typically involves a cumbersome data collection process (e.g. collecting building plans, information on constructions, and energy systems, etc.) and high financial impacts to the account of building owners, resulting in very low retrofitting rates in Europe.

Based on this background, the objective of this study is to define a flexible methodology that allows for the identification of energy efficient building retrofitting solutions for any kind of building within a neighborhood. The hurdle of data collection is reduced through the utilisation of already available building and census databases that are integrated into the methodology. With this method, building owners benefit through easily accessable retrofitting suggestions for their buildings. Communities would also benefit by being made aware of most energy intensive regions within their area, facilitating improved masterplanning for future decision making at the community level.

Methodology

This paper presents a workflow to support the decision making for identifying building energy efficiency measures at the urban scale. The workflow (shown in Figure 1) includes: *i)* A method to extract geo-spatial information, including information on building characteristics and building energy systems, based on building and census data. *ii)* A method to evaluate time-dependent solar potential on roof surfaces *iii)* A method to evaluate current and future energy demands of buildings using an automated process developed in Matlab to deploy EnergyPlus at urban scale, that includes a connection to geo-spatial information and facilitates the computation of energy demand profiles for different scenarios at individual building level.

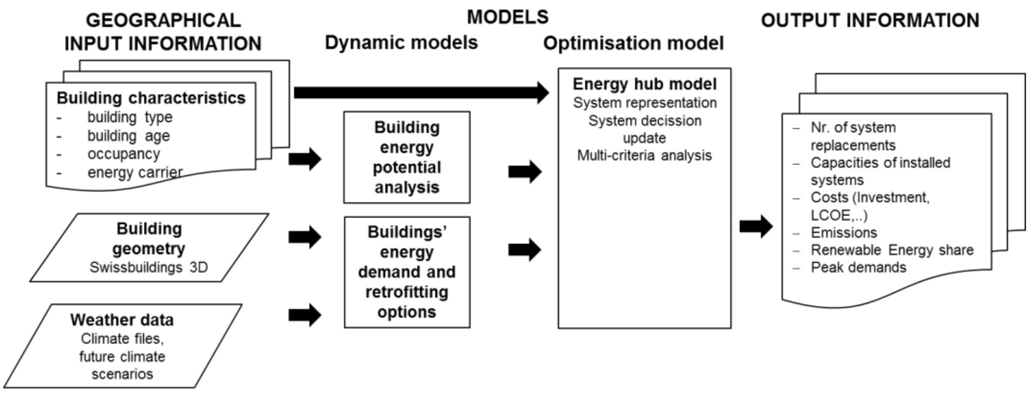


Figure 1: Multi-criteria decision making analysis workflow.

And finally, *iv)* an updated version of the energy hub model to evaluate best performing options in terms of retrofitting and energy system updates, based on objective functions. As a result, input information on existing buildings, including their system state, is integrated into the energy hub model. The tool allows for the evaluation of individual building level solutions, and is additionally able to take renewable energy potentials and boundary conditions of the neighborhood into account. The developed method is applied on a case study pertaining to an existing rural area. Modelling results include best performing options in terms of CO_2 emissions while minimizing the resulting costs of energy system solutions.

Geo-spatial information

To describe the current situation of buildings within a neighbourhood GIS based building information is required such as building layout, building characteristics and environmental information. Relevant input information is collected from diferent sources, such as building statistical data from Switzerland (BFS 2013), 3D building information (Swisstopo 2016), weather information (Meteotest 2016), etc. Relevant attributes as well as information on data processing for model input information is summarized in Table 1.

Table 1. GIS based information

ATTRIBUTES	SCRIPTS, METHODS, STANDARDS	MODEL INPUT INFORMATION
EGID number	Building coordinates	Building location
Building geometry- 3d information	Scripts to represent building geometry in building energy models	Layout, building height, thermal zones, adjacencies
Building geometry-Roof surfaces	Scripts to represent building geometry and inclination of roof surfaces	Input for Solar on roof surfaces
Building age	Classifies age category, assigns certain typical building construction characteristics such as U-values	Construction information
Building type	SIA standards 2024	Appliances, occupancy and lighting assumptions
Nr. of occupancy	SIA standards 2024, script on variability at urban scale	Occupancy profile
Energy carrier	Classifies type of heating system (statistical information)	Efficiency of heating system

Building energy potential modelling

A method to identify the building integrated renewable potential pertaining to the utilization of the solar resource is developed. Therefore a GIS based approach has been developed to derive the hourly solar radiation that is incident on building rooftops. A digital elevation model (DEM) of the area was created taking the surrounding topography and buildings into account. Next step, suitable areas for PV installations were derived. Depending on slope and orientation of the building rooftops, non-suitable surfaces were eliminated. These include, for example, north oriented roof surfaces and roof slopes with an angle higher than 70°. The solar radiation incident on each rooftop was then calculated. The "solar analyst model" (Fu and Rich 1999) which is integrated within the ArcMap environment by ArcGIS is used. The "solar analyst model" creates an upward-looking view shed, which is then overlaid with sun maps, representing the position of the sun in the sky through time, and sky maps, consisting of a series of sky sectors for which diffuse radiation energy is calculated. To derive diffuse radiation energy, atmospheric values including transmissivity and diffuse ratios are required, which are calculated for the specific location from an available weather file. Finally, solar radiation is calculated for each cell and for each hour, which is further processed to average hourly solar radiation values for each building (Mavromatidis et al. 2015).

Buildings energy demand modelling

To represent the current situation in terms of energy demand pertaining to heating, cooling, electricity and domestic hot water a bottom up modelling framework is developed. The method enables to compute hourly energy demand profiles for multiple buildings within a neighbourhood. The building simulation models are based on building floorplans, their height (2.5D shape) and a set of additional geo-spatial information to derive relevant building characteristics. A flexible methodology is developed which allows to model any kind of neighbourhood or city within Switzerland and subsequently assess different retrofitting improvement options. Collected information on geometry and building characteristics is further processed to define input information (IDF-files) for the simulation tool EnergyPlus for each building separately, considering shading of neighbouring buildings. The simulation engine EnergyPlus (U.S. Deparment of Energy 2016) is a detailed dynamic energy analysis and thermal load simulation tool, which is capable to simulate integrated loads and system plants in the same time step. The advantage of applying an already well established building simulation tool at the urban scale lies in the possibility to abstract the physical representation of buildings in a simplified way, but also to more accurately model a building if needed. Figure 2 shows the workflow of the demand methodology.

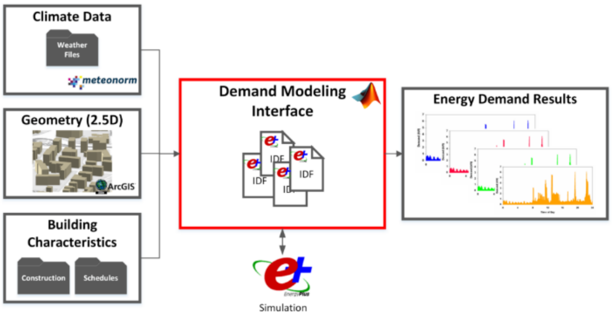


Figure 2. Workflow and modelling concept

Climate data Dependent on the neighborhoods location, information on weather conditions such as hourly air temperatures, wind speeds, and solar radiation, etc. are derived from climate files.

Building Geometry with relevant parameters such as thermal zones, building orientation and shading by neighbouring buildings are implemented in the modelling framework. Thereby accessible geographical building information from Swiss 3D buildings geodata (Swisstopo) (Swisstopo 2016) is pre-processed through a Geographical Information System (e.g. ArcGIS), defining the geographical coordinates of the floorplan vertices. Based on the actual building floorplan and building height, three dimensional thermal zones for each building are created taking floors, walls, roofs and window constructions into account. Geodata of Swiss 3D buildings define not only the building size and shape itself, but also the absolute geographical location and orientation of each building. This provides abundant geometrical information for any specific building in a neighbourhood. Additionally, it allows to study the interaction among buildings in terms of external shading. According to global geographical coordinates, buildings in a neighbourhood are clustered within a user defined area from the central building as the origin. Within each simulation run the central building is modelled in detail assuming typically one zone per floor, thereby accounting for multiple thermal zones within a building. Neighbouring buildings are defined as shading objects in order to account for local shading through buildings but also for reflections from beam and sky solar radiation from exterior surfaces. The radius of the area can be modified within the model to fit the building density of the district. Figure 3 shows the 2D footprint of an example building and its neighbourhood as well as the resulting IDF file generated by the DM and visualized in SketchUp.

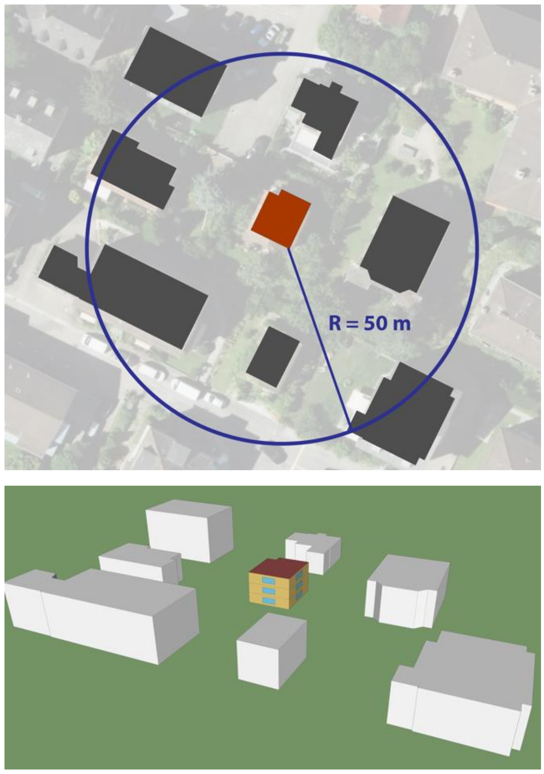


Figure 3. Example model input (2D footprint) and visualization of the generated corresponding EnergyPlus model of a building and its neighbourhood represented as shading objects

Building Characteristics Additional building characteristics are identified. Relevant input information pertains to building construction, type and usage, as well as building systems, glazing ratios and infiltration rates. The suggested modelling approach builds on Census data and Swiss building statistics (BFS 2013) where for each building in Switzerland information on the building construction year, current heating and domestic hot water systems and building type is available (Table 1). In order to use this information for building simulation, information has to be further processed. However, reliable input information for most of the required building characteristics, which is consistently available throughout Switzerland, is difficult to retrieve at individual building level without a detailed analysis. Therefore, an archetypical approach which clusters buildings according to building location, type of building, and year of construction is considered. This archetypical approach defines material properties, construction settings, glazing ratios and infiltration rates for groups of buildings of a similar building type (e.g. Residential, Office…) and of a certain construction year period. Construction methods changed considerably over time and thus also the resulting heat transfer coefficients (U-Values). A categorization which clusters construction types depending on the year of construction was adopted. In the model, construction information from literature is integrated.

Internal Conditions Building energy simulation require additionally information on building's internal conditions pertaining to the presence of building occupants and their activities, as well as indoor environmental control requirements. These inputs are a combination of scalar values, like the floor area per person (m^2/P), lighting and equipment power density (W/m^2), and temporal information such as schedules on occupants' presence and the utilisation of lighting and equipment. Additional information includes heating and cooling set points, their temporal variation, and the ventilation rates. Such information is very well standardized at building level in Switzerland, according to the norm SIA 2024 (SIA 2006). Based on available information, a database was developed for different room types, and further aggregated to building level, which is then linked to the simulation engine.

Applying the same information with the same user behaviour and the same lighting and appliance densities among all the buildings, would result in an overestimation of peak hourly load at larger scale. An approach is required which introduces variations in schedules between buildings and which takes the simultaneity factor into account.

Starting from the scalar input parameters, the norm SIA 2024 provides nominal values as well as a range in which they are expected to fall. Using this information, a triangular distribution is proposed with the nominal value being the distribution's mode. This way, sampling different values for different buildings is possible and, thus, the introduction of the expected variability in a building stock.

Additionally, SIA 2024 provides typical daily schedules for occupancy and appliance usage, which are usually assumed to be repeated for each day of the year. Starting from this 'nominal' yearly schedule, we introduce the desired variability in two ways: the first is labelled as vertical variability and it consists of randomly perturbing each hourly value around its nominal value (e.g. by $\pm$15%). The second way is labelled as horizontal variability. The approach consists of the creation of blocks of hourly periods for the 24 h of each day and within these blocks shuffling the nominal schedules values with each other. By repeating this process for each building type, we create a bank of all the schedules required, from which we can sample a different schedule for each building, hence, creating a variation among buildings in the temporal dimension as wel. Figure 4 shows an example of variying profiles.

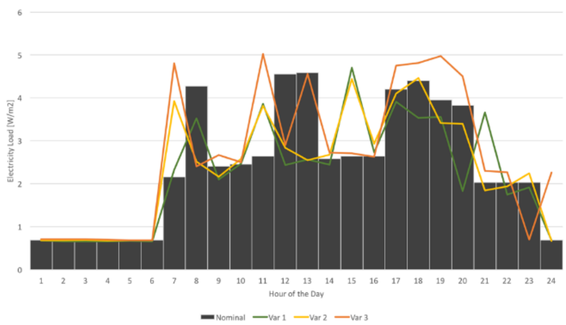


Figure 4. Nominal floor area specific electricity load for appliances and three different variations

Retrofit of Building Envelope The model can be used to evaluate different envelope retrofitting options. In case of a retrofit of the building envelope, additional insulation is added to the original constructions until required U-Values for retrofitted constructions according to SIA 380 are met. Additional envelope retrofitting options include replacement of windows, partial retrofitting of individual constructions, such as roofs or facades, and whole building retrofitting solutions which combines all the different measures. The resulting retrofit constructions are structured in a database similar to the non-retrofitted constructions and linked with the model.

Simulation results Results are computed for individual buildings at an hourly resolution, including actual and future demand for heating, domestic hot water, cooling and electricity, as well as annual primary energy consumption and GHG emissions for operation of the building. Besides operational energy, embodied energy and economical aspects of retrofit measures are analysed in detail.

Energy hub modelling

To select the optimal combination of both building envelope retrofitting options and energy supply systems to provide electricity, space heating and DHW the energy hub approach is used. The energy hub approach is a MILP optimisation framework which can be used to optimize energy systems for buildings, neighborhoods, regions or country scales. The approach which has been applied here in this paper is based on the formulation of Mavromatidis et al. (2014). The following types of constraints are implemented using AIMMS:

- 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

Table 2. Information on energy system parameters including unsubsidised fixed and capacity dependent costs, lifetimes, minimum capacities and efficiencies. Heat pump efficiencies are varying for space heating (SH) and DHW.

Techn-ology	**Fixed Cost [CHF]**	**Linear Cost [CHF/ kW]**	**Life-time [years]**	**Min. size [kW]**	**Effi-ciency**
Biomass boiler	27’800	860	20	10	0.85
GSHP	20’000	2’380	20	5	4 (SH) 2.75 (DHW)
ASHP	18’300	1’020	20	5	3 (SH) 2 (DHW)
ST	4’000	1’000 [CHF/m²]	25	4 [m²]	0.7
PV	900	400 [CHF/m²]	30	5 [m²]	0.15
Electrical heating	14’600	730	30	-	1
Oil boiler	26’600	570	25	10	0.85

The energy hub including technologies which are taken into consideration within this study are shown in Figure 5, with inputs I and outputs L. Typical residential energy conversion and storage systems are considered: Air (ASHP) and ground source heat pumps (GSHP), biomass and oil boilers, photovoltaic (PV) and solar thermal (ST) panels. Additionally, the change of heating distribution system, which is required for certain systems is considered (Wu et al. 2017). A DHW tank is assumed to be present in all buildings, sized according to the number of inhabitants. The building envelope retrofitting scenario is implemented as an additional decision variable within the energy hub optimisation.

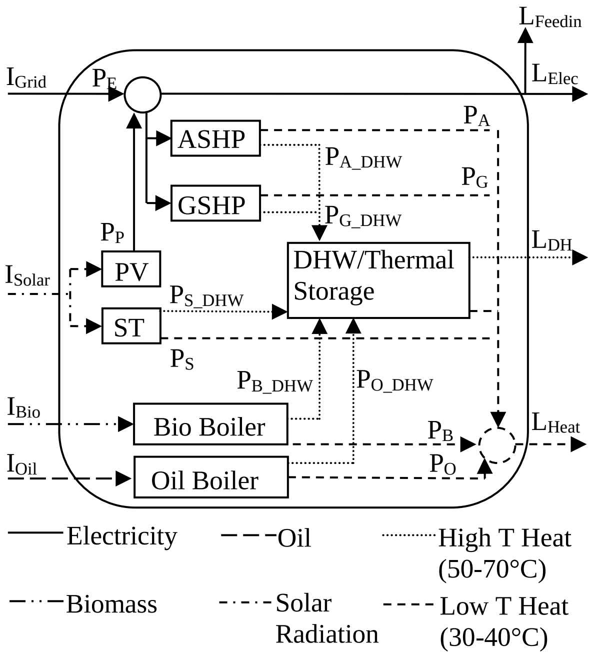


Figure 5. Energy hub layout

Two types of objective functions are considered in this study, namely annualised costs and life cycle environmental impacts. To evaluate multiple objectives in as single-objective mathematical programming framework the epsilon-constraint method (Haimes et al., 1971) is utilized.

Cost objective function: Each energy conversion technology T contributes to the financial objectives 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 defined as:

$$o_1 = \sum_T([fc_T - fs_T] * y_T + [lc_T - ls_T] * cap_T)/a_T + \sum_t(\boldsymbol{i} * \boldsymbol{c} - l_{feedin} * c_{feedin}) + c_R/a_R \quad (1)$$

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

Investment and retrofit (c_R) costs are annualised with the factors a, using the equivalent annual cost method, considering their lifetimes τ and a yearly interest rate r:

$$a = \frac{1 - \frac{1}{(1+r)^{\tau}}}{r} \quad (3)$$

Life cycle environmental impacts: Nonfinancial objectives such as life cycle GHG or primary energy (PE) are evaluated per unit of delivered final energy, or massspecific for retrofit materials. Therefore, the nonfinancial objective functions can be expressed as the products of all conversion outputs with their impact factors $\mathbf{f_E}$ summed over time, and the impact of all retrofit materials R with their masses (m_R), impact factors (f_R) and lifetimes (τ_R):

$$o_2 = \sum_t (\boldsymbol{p} * \boldsymbol{f_E}) + \sum_R (m_R * f_R)/\tau_R \qquad (4)$$

Assumed energy system parameters such as cost values and assumed efficiencies are summarized in Table 2.

Case Study

The presented method is applied on a case study. The village of Zernez (figure 6) is located at an altitude of 1474 m with a mean annual temperature of 4.8 °C and horizontal solar radiation of 1170 kWh.m^{-2}. It has about 1150 inhabitants and comprises of approximately 300 buildings. Buildings vary in terms of age (between 1600 and 2010), type (residential, retail, hotel, etc.) and heating system (oil heating, district heating network, electric heating, etc.) (see Table 3). For the modelling 100 residential buildings are selected which are modelled using the modelling framework. More details on the case study are provided in Orehounig et al. (2014).

Figure 6. Image of the village

Table 3. Construction periods of houses

PERIOD	HOUSING	HOUSING+ TRADE	HOTEL	Σ
- 1900	32	15	5	52
1900-1945	1	2	0	3
1945-1969	7	3	0	10
1970-1989	21	4	0	25
1990-2014	9	1	0	10
Σ	70	25	5	100

Results and Discussion

In a first step solar potential on roof surfaces is modelled using the described framework. Figure 7 shows the resulting available area for photovoltaic installations per buildings, and figure 8 shows the raster solar map for the different cells on building roofs (Mavromatidis et al. 2015).

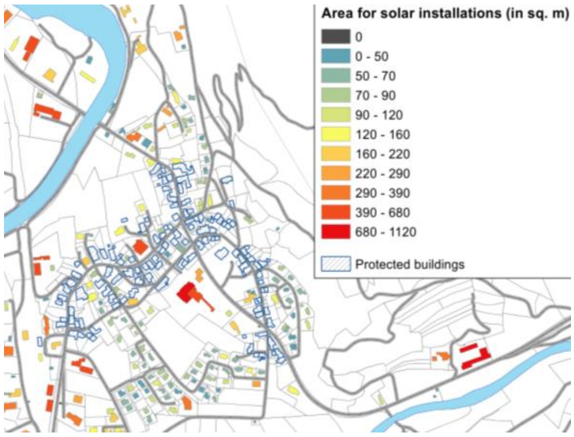


Figure 7. Available area for photovoltaic installations per building. Protected buildings are framed with a blue border

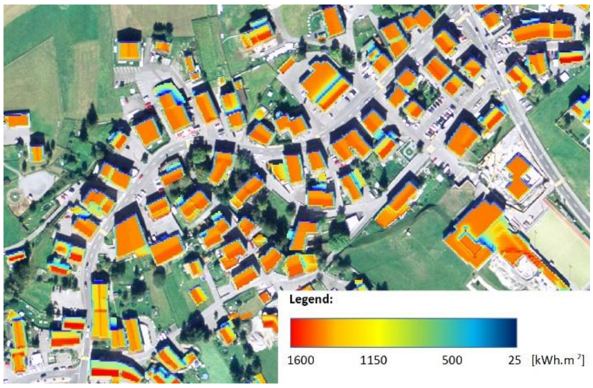


Figure 8. Raster solar map for the different cells corresponding to the building roofs

As for computing the energy demand of buildings pertaining to space heating, domestic hot water and electricity the demand modelling framework is deployed. Results are computed for each individual building within the urban neighbourhood. Figure 9 shows specific energy demand for all buildings for space heating, domestic hot water and electricity. Different envelope retrofitting strategies are integrated in the demand modelling framework, which allows to compute the future energy demand under different conditions. Therefore, modelled buildings are categorized in terms of their age, size and current heating system. 11 typical buildings, ranging from detached single family homes (D) to semi-detached (SD) and large multifamily houses (L), built between 1870 and 1999 are selected to represent the different categories. Buildings are referred to by their size and construction period, i.e. D-1900 for a detached building, built before 1900. Figure 10 shows for this selection of buildings the current annual heating load "base" as well as future conditions assuming that roof, windows, facades or the whole building is retrofitted. Thereby two different scenarios are implemented pertaining to a "limit" scenario and a "target" scenario as per the Swiss building code SIA 380 (SIA 2009).

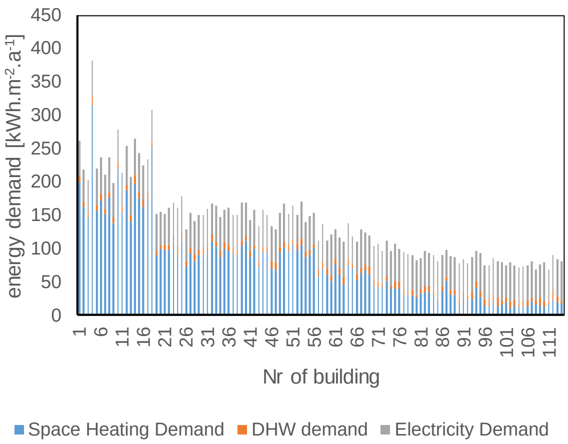


Figure 9. Energy demand for space heating, domestic hot water and electricity for all modelled buildings sorted by energy demand

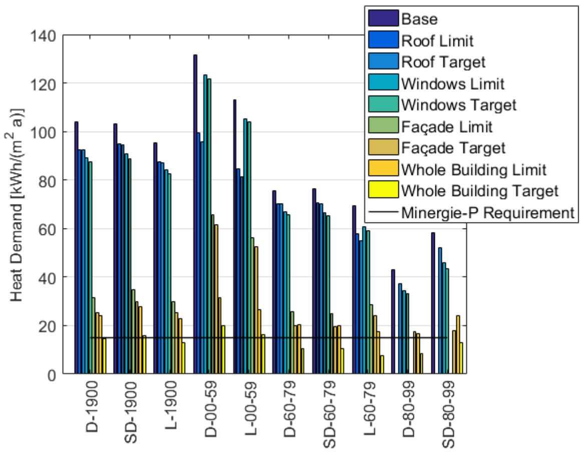


Figure 10. Simulated heating demands of all buildings.

Geospatial information as well as renewable potential and demand data are further used as input information for the energy hub modelling framework. For a selected set of buildings single objective optimization runs are performed for costs and GHG emissions.

Figure 11 depicts cost optimisation for building D-60-79 as an example for an oil heated building with relatively low initial insulation levels. Changing 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) leads to 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.

The corresponding GHG emissions in Figure 11 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 significant drop as soon as the façade is retrofitted.

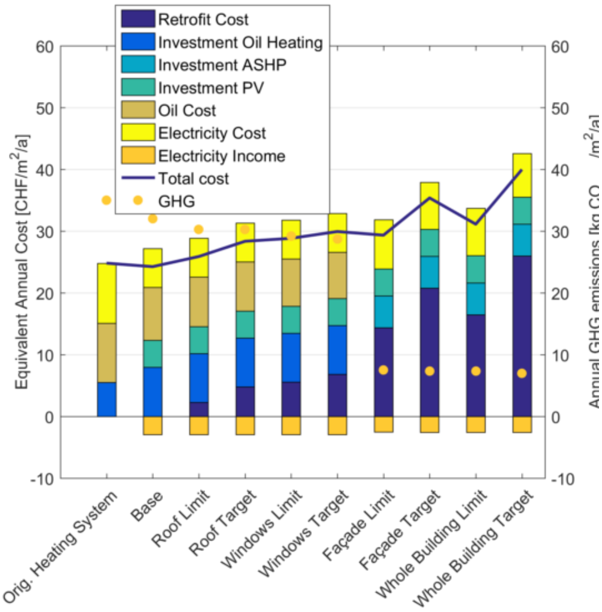


Figure 11: Single-objective cost optimisation results for all retrofit scenarios of building D-60-79. Dots and the line show total costs and GHG emissions, bars show the cost breakdown for each technology and retrofit.

When optimising the same building for GHG emissions as depicted in Figure 12, a combination of biomass and PV panels is found. Changing 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.

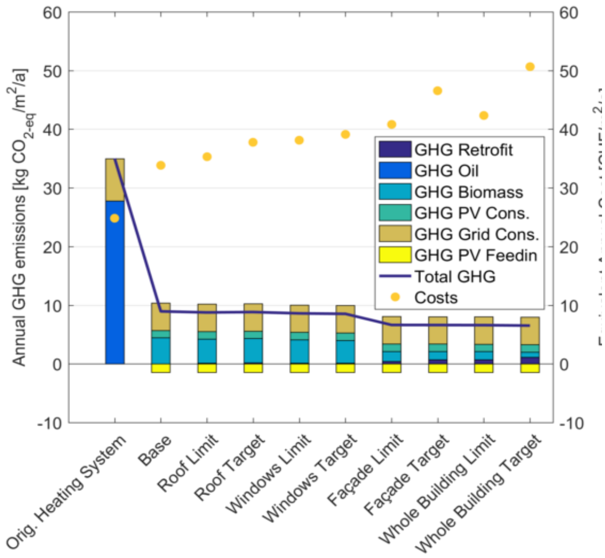
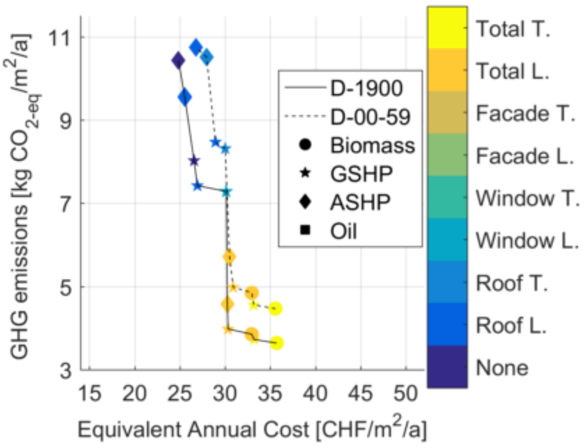
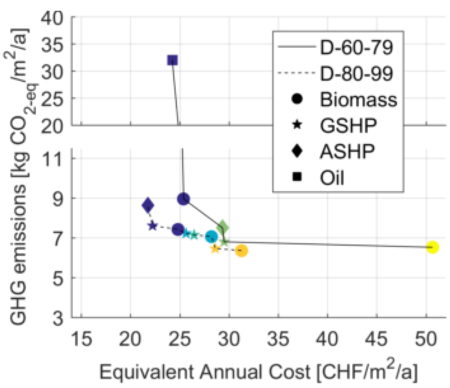


Figure 12: Single-objective GHG optimisation results for retrofit scenarios of building D-60-79. Dots and the line show total costs and GHG emissions, bars show the GHG emission breakdown for each technology and retrofit.

Additionally to single objective optimization, multi-criteria runs are performed. Figure 13 shows the cost and GHG pareto fronts for 4 example buildings based on the optimal system and retrofitting interventions. For all buildings, the best performing option in terms of CO_2 is a biomass based heating system with a combination of different building envelope retrofitting interventions. Results further suggest that 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. Computing the results at individual building level allows for the benchmarking of solutions against the targets of the Swiss Energy strategy, which suggests that 80% of the buildings within the district need to be retrofitted by 2050 in order to reach the emissions targets.



a) Before 1960



b) After 1960

Figure 13: Cost - GHG multi-objective pareto fronts for all detached buildings.

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 significant slope changes, indicating that the costs to reduce GHG emissions further can change dramatically depending on the location on the pareto front.

Conclusions

This paper demonstrates an approach how the energy transitions can be supported by a collection of tools and databases for individual buildings in a neighborhood. The workflow consists of a method to extract geo-spatial information, compute renewable potentials and energy demands and an optimization model to evaluate the most suitable retrofitting scenario in terms of envelope and system update based on multi-criteria decission making. The approach can be easily applied to residential buildings in Switzerland. Results are computed for a rural village to demonstrate the method. Results of the case study show that the optimal transformation strategies depend on the original heating system, while age and size of the building influence the achievable GHG emissions and related costs.

Acknowledgement

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