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ANALYZING THE POTENTIAL OF LOW EXERGY BUILDING REFURBISHMENT BY SIMULATION

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ABSTRACT

Providing thermal interior comfort in buildings in temperate climate zones is an energy-demanding task that can be optimized through refurbishment. We compare four refurbishment strategies to convert an existing residential building with high primary energy demand into a low-exergy building. The strategies differ in the balance of passive and active refurbishment measures, respectively in the balance of improving the building envelope and installing low-exergy building systems. We rate the refurbishment strategies for their sustainable effectiveness by comparing the impact on overall exergy consumption, embedded and operational emissions, costs and aesthetic value. Our results show that the refurbishment strategies with greater focus on the active components and minimal improvement of the building envelope are the most promising ones.

INTRODUCTION

Recent studies estimate that the building sector consumes 38% of the total available primary energy and up to 50% of the total produced electricity, which relates to around 34-40% of the worldwide CO2 emissions (Price et al, 2006, Ürge-Vorsatz et al, 2007). Due to cheap primary energy prices during the period after 1945 until now, the buildings have been designed for providing interior comfort regardless of the exergetic efficiency of the systems. Rising costs and the finite nature of fossil fuels as energy carriers to provide electrical current and heat created a demand for alternative energy sources. Confronted with the damaging effects on the environment, namely global warming caused by burning great amounts of fossil fuels and radioactive contamination due to the unsolved disposal problem of nuclear waste, the regulations for many sectors of the industry have been tightened to introduce more energy efficient products (UNEP, 2007). Especially the building industry is facing changes, since a huge potential for CO_2 emission reductions at low costs exists in this sector (IPCC, 2007).

This has lead to a multitude of government-funded programs favoring the concept of low-energy houses. Focusing on a reduced heat transfer through the envelope, these programs aid primarily the increasing of the thermal resistance of the building envelope, i.e. with thicker thermal insulation and tripled glazed windows, with questionable aesthetic constraints. The programs mainly favor passive solutions (Minergie, 2011, Passivhaus, 2011). The attributes of the passive components in a building, for example the thermal resistance, typically cannot be altered after the installation to respond to fluctuating climatic conditions and to reduce the overall energy demand of buildings. In order to avoid wasting tons of resources, producing embedded emissions and limiting the design, we propose to shift the focus onto the exergetic efficiency of the active components for heating, cooling, domestic hot water generation (DHW) and ventilation installed in the building.

We present this idea by comparing four variants of a refurbishment project. These four variants have the same geometry, usage and demand, but use different combinations of passive and active components to provide the same interior thermal comfort. The possible scenarios for heating, cooling and DHW generation of the dual-family residential building require a dynamic building simulation, which we implemented in Trnsys 17 (Trnsys, 2011). Based on the results, we present the different net primary operational energy demands. Additionally, we determine the embedded emissions of each case with the life cycle assessment software Simapro 7.2.4 (PRé Consultants, 2011). We analyze the refurbishment and operational costs with a building construction cost index BKI and we discuss the aesthetic consequences of each design.

THEORETICAL BACKGROUND

Current methods for heating buildings can be classified in either high- or low-exergy methods. The prevalent form of high exergy systems consists of burning fossil fuels. These systems reach Carnot efficiency factors of up to 95% at the boiler, but also produce temperatures of around 500°C (Meggers, 2009). This is far beyond the effectively required heating temperature of around 30-70°C, depending on the heat distribution system. Since the majority of the exergy content remains unused, while it is transformed into anergy without providing work, these systems have a low exergetic efficiency. Contrary to this, low exergy systems combine the freely available energy from low exergetic sources with temperatures between 5-15°C and lift it to the desired outgoing load temperature of 30-70°C. The smaller the difference between sink temperature, T_{hot}, and surrounding temperature, T_{cold}, the smaller the exergetic value of the heat flux. Low temperature systems avoid the temperature mismatch of the high exergy systems, as T_{hot} exceeds by just 10-20°C the room temperature. Additionally, these systems lead to a high exergetic efficiency, since more heat is put out than exergy is put in.

In general the focus of our research group is on finding methods and developing components that enable low-exergy systems. For this paper we have studied four variations of the same refurbishment project, a two storey dual-family house operating with a heat pump connected to a vertical geothermal heat exchanger.

According to N.L.S. Carnot, the maximal heat that can be provided by the invested work in a thermal process of a heat pump is expressed by the COP_{ideal}, which depends on the temperature lift between the cold source, T_{cold} and the hot sink, T_{hot}, as expressed in equation (1). The COP_{real} of equation (2) takes into account that the maximum value of the COP_{ideal} is reduced by the quality of the heat pump through the value g. The total efficiency of the heating system is calculated by taking into account the electricity consumption of all required system components for heating. It is expressed by equation (3) with the seasonal energy efficiency ratio, $SEER$, that relates the total annually delivered heat, Q_h, to the integrated electricity demand, P_{el}, of all system components that are required for heating, like additional pumps, valves etc., typically for a full annual cycle. In reaction with the environment, the exergy content, $\dot{Ex}$, of the heat, $\dot{Q}_h$, is consumed and transformed into anergy, $\dot{An}$, i.e. energy that cannot perform work. This is a direct result of the first and second law of thermodynamics, stating that the total amount of energy, expressed as heat, Q_h, in equation (4) is not changed, only transformed. However, the quality is constantly reduced as energy flows in a thermodynamic cycle from a hot source to a cold sink in order to perform work. The exergy content, $\dot{Ex}$, of a heat flux, $\dot{q}$, can be determined by using equation (5), respectively the anergy content, $\dot{An}$, by equation (6) (Moran et al., 2000, Ahern, 1980).

$$COP_{ideal} = \frac{1}{\eta_{carnot}} = \frac{T_{hot}}{(T_{hot}-T_{cold})} \qquad (1)$$

$$COP_{real} = \frac{Q_h}{W} = g \cdot COP_{ideal} \qquad (2)$$

$$SEER = \int_{t1}^{t2} \dot{Q}_h \cdot dt \;/\; \int_{t1}^{t2} P_{el} \cdot dt \qquad (3)$$

$$Q_h = Ex + An \qquad (4)$$

$$\dot{Ex} = \dot{q} \cdot \eta_{carnot} = \dot{q} \cdot \frac{1}{COP_{ideal}} = \dot{q} \cdot \left(1 - \frac{T_{cold}}{T_{hot}}\right) \qquad (5)$$

$$\dot{An} = \dot{q} \cdot (1 - \eta_{carnot}) = \dot{q} \cdot \left(\frac{T_{cold}}{T_{hot}}\right) \qquad (6)$$

Applying this concept to the building systems enables us to rate the methods to provide comfort in the building in terms of their exergetic efficiency with equation (4). The smaller $\dot{Ex}$ is, the higher the exergetic efficiency of the building system is (Meggers, 2011).

The concept of low exergy has been taken up by many research fields, including the building science, e.g. with the IEA ECBCS Annex 37 and Annex 49 and it motivated the development of optimized Low Exergy (LowEx) building systems at the Chair of Building Systems, ETH Zurich, (Meggers, 2011).

METHOD

In order to assess refurbishment strategies we performed dynamic simulations in Trnsys on a dual-family home. We analyzed four refurbishment strategies, each with different combinations of active and passive refurbishment measures. In general, the lesser the thermal resistance of the envelope is, the greater the investment in the exergy-efficient building systems must be to provide thermal comfort. This results in different annual heating/cooling demands, but also in more or less exergy efficient systems. As the heating demand is more relevant in the temperate and continental climate of Switzerland, the studied buildings are classified according to their heating demand, for example as Dual-Family-Home-100 (DFH100) with an annual heating demand of Q_h=100kWh/m^2.

Passive system components

We consider the envelope of the building type DFH100 as the initial building shell. This type, with no changes to the envelope, requires the most comprehensive building system. The DFH60 has minimal changes to the façade. Only the windows are exchanged for windows of higher thermal resistance (R-value) and lower solar energy transmittance (solar heat gain coefficient, SHGC). The DFH45 is very similar to the DFH60, but with an additional thermal insulation of the roof. Contrary to the other three types, which have a constant ratio of transparent and opaque areas of all façade area, the type DFH15 requires a restrictive glazing ratio, GR, depending on the orientation. The design of the DFH15 is conform to the strictest energy saving standard of Switzerland, Minergie-P, which demands a high quality envelope, in respect of thermal and airtightness. The material qualities of the envelope are listed in Table 2.

General aspects to geometry etc. of the buildings are listed in Table 1. The building characteristics are motivated by the work of Dott et al., 2011.

Table 2: Areas of the passive building components

Units [m^2]		DFH 100	DFH 60	DFH 45	DFH 15
Roof / ceiling / floor		108	108	108	108
Glazed façade	North	14.4	14.4	14.4	3.6
	West	10.8	10.8	10.8	5.4
	South	14.4	14.4	14.4	14.4
	East	10.8	10.8	10.8	5.4
Opaque façade	North	93.6	93.6	93.6	104.4
	West	61.2	61.2	61.2	66.6
	South	93.6	93.6	93.6	93.6
	East	61.2	61.2	61.2	66.6
total exterior facade area		360	360	360	360
Basement wall	North	36	36	36	36
	West	27	27	27	27
	South	36	36	36	36
	East	27	27	27	27

Table 1: Quality of the passive building components

	typically Units [m]	DFH 100	DFH 60	DFH 45	DFH 15
Roof	Plaster Inside	0.015	0.015	0.015	0.015
	Concrete	0.280	0.280	0.280	0.280
	XPS Insulation	0.070	0.070	0.170	0.240
	Bitumen	0.005	0.005	0.005	0.005
Basement ceiling	Wood flooring	0.015	0.015	0.015	0.015
	Floor screed	0.120	0.120	0.120	0.120
	EPS Insulation	0.020	0.020	0.020	0.020
	Concrete	0.160	0.160	0.160	0.160
	EPS Insulation	0.060	0.060	0.060	0.220
	Plaster inside	0.015	0.015	0.015	0.015
Exterior wall	Plaster inside	0.015	0.015	0.015	0.015
	Exterior brick wall	0.210	0.210	0.210	0.210
	EPS Insulation	0.060	0.060	0.060	0.240
	Plaster outside	0.003	0.003	0.003	0.003
Window +frame	R-value [(m^2·k)/W] / SHGC [-]	0.33 / 0.755	1.0 / 0.584	0.66 / 0.609	1.0 / 0.586
Interior Circulation wall	Plaster inside	0.013	0.013	0.013	0.013
	Interior brick wall	0.200	0.200	0.200	0.200
	Plaster inside	0.013	0.013	0.013	0.000
	Plaster insulating	0.000	0.000	0.000	0.030
Basement wall	Plaster inside	0.015	0.015	0.015	0.015
	Brick wall	0.210	0.210	0.210	0.210
	XPS Insulation	0.060	0.060	0.060	0.060
Basement floor	Wood flooring	0.015	0.015	0.015	0.015
	Floor screed	0.060	0.060	0.060	0.060
	Concrete	0.150	0.150	0.150	0.150

Active system components

The equation (1) and (2) express that the heat pump cycle can be optimized on both ends, by the source and the sink temperature. Lowering the sink temperature requires low temperature heating panels with a large surface area. The source temperature depends on the used heat source. However, a low temperature lift also requires a low temperature lift heat pump. Research has demonstrated that a COP_{real} of 10 with current technology for a low temperature-lift heat pump is possible (Wyssen, 2010). As expressed with equation (5), the required exergy, which is delivered in form of electricity, in a system with a COP_{real} of 10 combines one unit of electricity with 9 units of heat from the low exergy source. Compared to currently commercially available systems, with a COP_{real} of approximately 4, LowEx systems can reduce the exergy demand by 50% or more. In the temperate climate of Switzerland ground-coupled heat pumps can be used to achieve such a high COP_{real}. They typically operate with double u-tubes.

The new borehole design, as shown in Figure 1c, is based on the double u-tubes called dual-zone borehole (DZB). The DZB consists of two u-tubes of different length, i.e. a deep u-tube and a short u-tube in one borehole. The upper part of the deep u-tube is insulated for the whole length of the short u-tube, allowing for a stratified ground storage consisting of two temperature levels. The short u-tube activates the cold storage for cooling and hot water production during the cooling season, whereas the deep u-tube activates the warmer storage for heating and domestic hot water production during the cold temperature season. Typically, the return temperature of the ground source heat exchanger rises linearly with the ground temperature, which depends on the geothermal temperature gradient, GTG. Below a depth of 20m seasonal fluctuations of the GTG are insignificant. Typically a GTG of 0.03 K/linear meter is assumed for the location Zurich (Kohl et al., 2007). This correlation of the depth of the borehole to the performance of the heat pump can be used to increase the source temperature and the COP_{real}. Thus, instead of optimizing the total borehole length based on the heat demand of the building (Bernier, 2002), we dimension the total borehole length solely based on the heat carrying fluid's return temperature. The short u-tube predominantly is used as a heat sink for cooling. The depth of this section depends on the peak-cooling load with a limit of 200 meters for effective passive cooling, as shown in equation (7).

$$l_{short-u} = \dot{Q}_{cool,peak}/q_{exp} < 200m. \qquad (7)$$

The drawback of deep boreholes is the higher pumping power to deliver the required pressure head. This affects the operational costs, which have been considered in the cost analysis of the LowEx building system. In general, depths greater than 450m are currently not recommended, since heavier drilling equipment is necessary, which significantly increases the total costs of the borehole construction.

Additionally to the basic requirement of a low temperature heat pump and a heat source to provide heating to a building, we considered further strategies to enhance the performance of the heating. The heating system based on deep boreholes can be combined with a hybrid solar collector, a.k.a. PV-T collector, which generates heat as well as electricity. Contrary to typical thermal solar collectors that generate heat with a high temperature of above 50°C, this type of collector provides heat with a relatively low temperature of 20-35°C. However, when considering a full seasonal cycle in temperate climate, the number of days with solar irradiation that generates low temperature exceeds the number of days with solar irradiation that generates high temperature heat. This affects the efficiency of the heat pump operation, as it more frequently increases the source temperature of the heat pump. The result is an improved $SEER$, which reduces the demand for primary energy as well as the heat-extraction on the ground storage. This surplus of heat also actively regenerates the lower zone of the borehole, whenever there is no direct demand for the heat pump. The DZB and the PV-T collector allow for multiple scenarios to provide heat for heating and DHW preparation as well as cooling, by shifting the valves as illustrated in the Schematic view of the energy flows of Figure 1b. Increasing the number of scenarios compared to systems without PV-T collectors leads to flexibility in the energy management, see Figure 1a. For example: The deeper zone of the ground storage can be regenerated at the same time as the rooms are cooled or hot water is generated. On the long term, this avoids losing the quality of the ground storage, as it preserves the average storage temperature at a stable temperature, which is often a problem for non-actively regenerated vertical boreholes.

The DZB and PV-T were only installed on the DFH100, DFH60 and DFH45, whereas the DFH15 was only equipped with a conventional 150m deep double u-tube borehole, as the focus of DFH15 is the minimization of the energy demand, in accordance with the passive house philosophy. DFH100, DFH60 and DFH45 on the other hand are designed using the optimized LowEx building systems, with varying passive systems quality. DFH15 additionally required a mechanical ventilation system. This is rather a necessity to avoid structural damage of the façade, resulting from a requested airtightness of the envelope, which prevents a natural exchange of air humidity.

All models are also equipped with a typical floor heating and with a hot water tank of 1080 liters that can store the hot water demand of 6 occupants with a daily demand of 60 liter each. The DHW is typically generated by the heat pump. Table 3 lists the key parameters of the building systems.

Table 3: Active building components

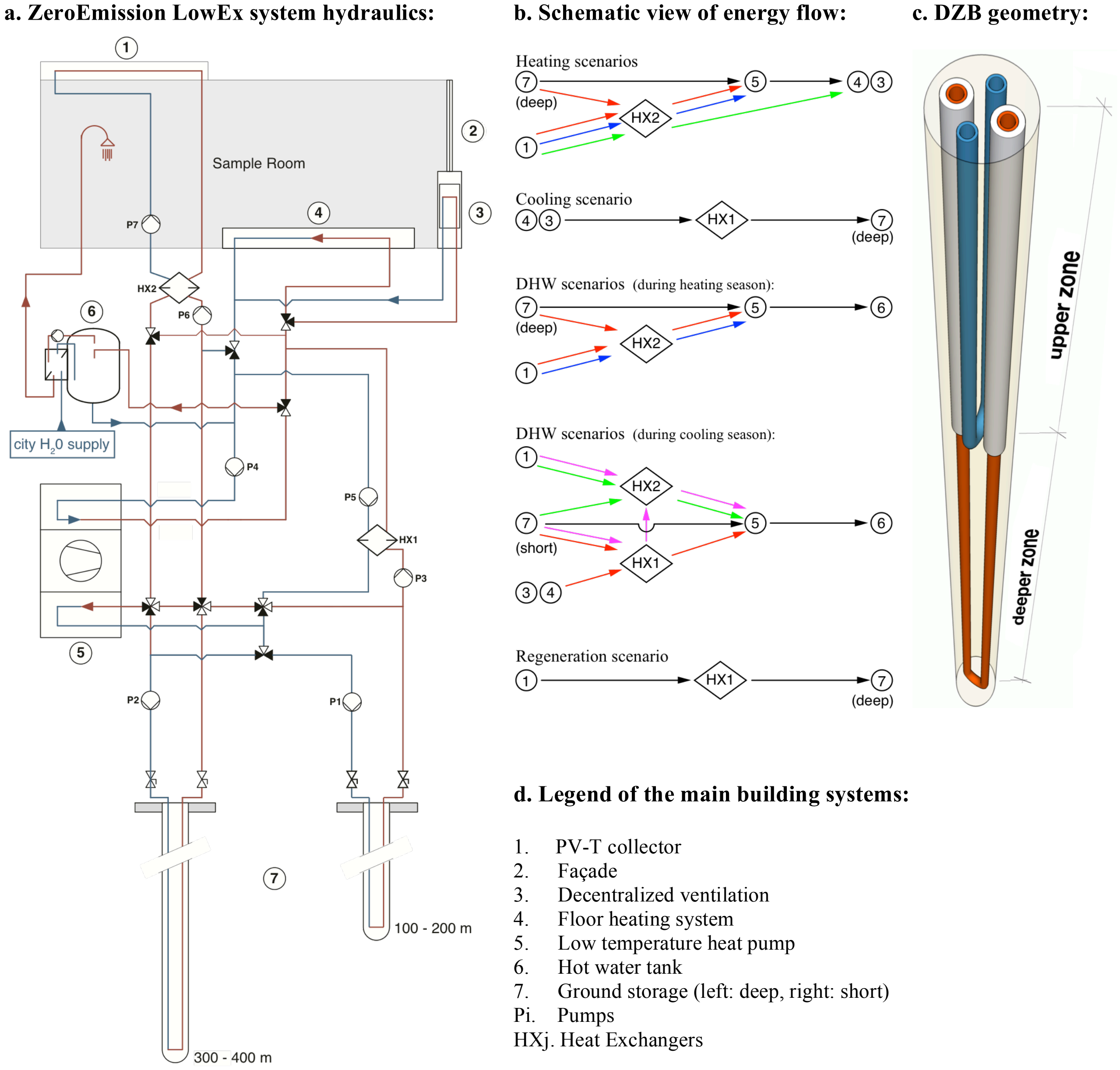
Component	DFH 100	DFH 60	DFH 45	DFH 15
Heat pump [kW]	11.6	8.6	7.2	3.9
Depth of deep u-tube [m]	400	400	400	150
Depth of short u-tube [m]	190	160	165	
PV-T collector [m^2]	75	50	38	0
Domestic hot water tank [m^3]	1080	1080	1080	1080
Pumping power deep u-tube [W]	300	300	300	200
Pumping power short u-tube [W]	100	100	100	
Pumping power floor heating [W]	30	25	20	15
Pumping power PV-T collector [W]	40	35	30	

Trnsys Implementation

The implementation of these four simulation models was done in Trnsys. The information of the passive building components as shown in Table 1 and Table 2 is used to compose the type-56. An active layer in the floor specification simulates the floor heating to provide heating. The exterior climatic conditions, required for the type-109, are based on the Meteonorm data file of Zurich-Kloten.

The storage parameters of the DZB are according to typical local conditions of Zurich (Kohl et al., 2007). The DZB is simulated with two independent ground storages of the type 557a, because of two reasons. First, the insulation of the upper part of the deeper u-tube prevents thermal transfer and minimizes the effect of the upper on the deeper zone. Secondly, the simulated average storage temperature oscillates around its initial storage temperature, because of the efficient management of both storages, which minimizes the vertical heat flux.

The PV-T collector was modeled with the type-50b. The parameters are according to real measurements of a PV-T collector developed at our lab, which will now be commercialized by the Swiss company 3S. The area of the PV-T collector on the roof is designed to fully regenerate the ground, thus avoiding the decline of the average storage temperature over the lifespan of the borehole, which would otherwise reduce the heat pump performance. The key characteristic of the PV-T collector is the unglazed front. As a consequence its performance is highly affected by wind velocity. Initial analysis in TRNSYS showed that using the standard wind velocities results in an underperformance of the PV-T


a. ZeroEmission LowEx system hydraulics: **b. Schematic view of energy flow:** **c. DZB geometry:**

d. Legend of the main building systems:

1. PV-T collector
2. Façade
3. Decentralized ventilation
4. Floor heating system
5. Low temperature heat pump
6. Hot water tank
7. Ground storage (left: deep, right: short)

Pi. Pumps
HXj. Heat Exchangers

Figure 1: On the left (a): A simplified scheme of the Zero-Emission LowEx model hydraulics / In the centre (b): energy flow as occurring for heating, cooling, DHW preparation and regeneration / On the right (c): the DZB geometry

compared to the actual measured results. This is due to the used wind velocities from Meteonorm, which are too high by approximately a factor of three, since the weather station collecting this data is located on an open field, whereas the PV-T collectors are mounted on roofs in an urban context common for Switzerland. Thus the used wind data has been adapted to the urban context with equations (8) (Wieringa, 1992) and (9) (Simiu et al., 1986).

$$U = \frac{U^*}{\kappa} \ln\left(\frac{z - z_0}{z_0}\right) \tag{8}$$

$$\frac{u^*_{city}}{u^*_{meteo}} = \left(\frac{z^*_{0,city}}{z^*_{0,meteo}}\right)^{0.076} \tag{9}$$

The heat pump was modeled with the type-668. The performance file is based on an actually installed low-temperature lift heat pump, however, the performance of the heat pump is linearly scaled to take into account the varying maximal heat load of each case. The peak of the heating load is critical for the cases DFH100, DFH60 and DFH45, whereas the peak of the domestic hot water preparation is decisive for the case DFH15.

The remaining hydraulics, i.e. pumps, valves and plate heat exchangers, were modeled using the Trnsys standard types. The power demand of the pumps is set according to the standard pump performance requirements (EMB, 2011). The controls are rule-based algorithms written in the TRNSYS equation block. The floor heating system and PV-T additionally require hysteresis controllers, type-2, in order to avoid the heat pump permanently switching on and off.

Installation and operational costs

The material and labor costs are determined with the construction cost index BKI and the BPL (BKI, 2011, BPL, 2011). A conversion factor of 1.38 allows for higher construction costs in Switzerland and especially in Zurich. We are aware that these are average costs that may vary significantly depending on the location of the site and the quality of construction. Thus, we assumed average refurbishment and installation costs of all passive and active components. We did not take into account governmental subsidies that are currently available to avoid financial distortion.

Embedded emissions

The embedded emissions for the construction and refurbishment phase of the four buildings were analyzed with the LCA software SimaPro version 7.2.4, using lifecycle inventory data from the Swiss ecoinvent database version 2.2. For the analysis we assumed a total building lifetime of 60 years for all four buildings. The lifetime of the main construction material (reinforced concrete and brick) therefore is 60 years, whereas for all other materials used in the passive building elements it is assumed to be 30 years. The passive building elements were modeled according to Table 1 and 2, considering construction and refurbishment of the elements. The active building elements analyzed were: floor heating (30 years lifetime), heat pump (20 years), borehole heat exchanger (60 years) and PV system (30 years).

RESULTS

Exergetic Performance

All four models can be classified as low-exergy models, with DFH15 also being a low energy house. Table 5 shows the key simulation results for the four cases. The energy load used for the domestic hot water is included in the heat transfer to load value.

The better the façade is, the smaller the required heating load to the building and the heat-extraction from the ground becomes. The heat transfer from the source is the effectively drawn energy on the sourceside. It exceeds the heat transfer from the ground, since it also includes heat from the PV-T.

The area of the PV-T collector on the roof is designed to fully regenerate the ground, and thus also correlates with the heat load. This has also the beneficial effect that the produced electricity exceeds the annual electricity demand of all building components.

Another interesting aspect, is that by simply changing the glazing, i.e. DFH60, one is able to reduce the cooling load more significantly than by also altering the building hull, i.e. DFH45. Of course this depends on the chosen window type and its SHGC value.

Costs

Although the total construction costs of the DFH15 are the lowest, the DFH45 has the lowest annual costs, as shown in Table 6. The most influential parameters of the annual costs are the life span of the components and the financial revenue from the electricity surplus. The average life span of the components is 32.1 years for the DFH15, respectively 55.6 years for the DFH60. Main reason is the different life span of the key components, which are the refurbished façade and the geothermal ground storage. Furthermore, the cases with solar collectors generate an annual surplus of electricity, which can be fed to the power network. This income is even more relevant to the cost-efficiency of each case than the assumed interest rate of the annuity, as shown in Table 4. In all scenarios, even assuming the surplus of electricity is fed without revenues (0.0 CHF), the DFH15 has the highest annual costs. The DFH15 would only become competitive assuming a charge for feeding electricity to the grid exists, listed as negative marginal cost.

Table 4: Marginal electricity costs to become lucrative, according to interest rates of annuity,

CHF / kWh electricity	DFH 100	DFH 60	DFH 45	DFH 15
Interest 3%	≥7.18	≥0.42	<0.42	≤ -1.04
Interest 4%	≥7.98	≥0.40	<0.40	≤ -1.16
Interest 5%	≥8.79	≥0.38	<0.38	≤ -1.29

Table 5: Simulation results for a one year simulation performed with the four models

Unit typically [kWh/a]	DFH 100	DFH 60	DFH 45	DFH 15
Cooling load	6.60E3	5.01E3	6.52E3	4.73E3
Heat transfer to load	4.41E4	2.83E4	2.14E4	1.30E4
Heat pump power demand	8.24E3	5.10E3	3.80E3	1.62E3
Heat transfer from source	3.59E4	2.32E4	1.76E4	1.14E4
Heat transfer from ground	3.23E4	1.99E4	1.43E4	9.98E3
Heat transfer to ground	3.70E4	2.63E4	2.22E4	4.12E3
SEER []	4.26	4.10	3.96	6.05
Heat generated by PV-T	3.64E4	2.53E4	2.15E4	-
El. generated by PV-T	1.04E4	7.36E3	5.85E3	-
El. demand of all aux. pumps	2.05E3 (19.9% of all)	1.77E3 (25.8% of all)	1.61E3 (29.7% of all)	530 (24.7% of all)

Table 6: Accumulated construction cost and annual costs, based on 4% mortgage rate and operational cost of 0.15CHF/kWh

Cost [CHF]	DFH 100	DFH 60	DFH 45	DFH 15
Active components	222'855	184'888	161'303	53'031
Passive components	-	2'553	13'952	117'614
Total costs	222'855	187'442	175'255	170'645
Annual costs	9'534	8'397	8'269	10'313

Table 7: Annual results of the environmental impact indicator Global Warming Potential (GWP) according to IPCC 2007 for all four buildings, Unit: [kg CO2 eq /year]

IPCC 2007	DFH 100	DFH 60	DFH 45	DFH 15
Passive (P) elements	1.73E+03	1.78E+03	1.87E+03	2.86E+03
Active (A) elements	9.71E+02	7.58E+02	6.55E+02	2.67E+02
P + A	2.70E+03	2.54E+03	2.52E+03	3.13E+03

Market Value

Even though the market value of each of the considered strategy is hard to determine, they are of great importance to the acceptance of the user. Assuming the PV-T collectors can be installed without altering the silhouette of the roofline, the strategy of DFH100 does not alter the original design of the building, which keeps or increases the market value. Exchanging the glazing, as proposed in DFH60, is also without effect to the design of the building. We assume the required additional thermal roof insulation of maximal 17cm for the DFH45 can be installed without raising the roof fascia.

The DFH15 requires clear aesthetic alterations. The glazing ratio needs to be changed accordingly to the orientation of the façade. This and the required 24cm of insulation on the opaque walls reduce the daylight factor inside. Former living spaces orientated to the North may loose their quality and view. However, the DFH15 also requires renewing the plaster of the opaque façade, which may be beneficial to the market value, if renewing of the plaster is required anyway.

Embedded Emissions

Table 7 shows the annual results of the environmental impact indicator Global Warming Potential (GWP) according to IPCC 2007 for all four buildings, considering construction and refurbishment during the buildings' lifetime of 60 years. The exterior wall contributes about 30% (DFH 100) to 42% (DFH 15) to the GWP of the passive elements. The PV system contributes about 66% (DFH 100) to 50% (DFH 45) to the GWP of the active elements. For the passive elements, DFH 15 has the highest impact in GWP, whereas for the active elements, DFH 100 hast the highest GWP. The GWP for the passive elements increases with the amount of insulation, so that DFH 15 has a significantly higher impact than the DFH 100 building.

CONCLUSION / DISCUSSION

Exergetic Performance

By using a PV-T collector optimized for low exergy buildings, we are able to keep the ground quality and avoiding a permanent temperature drop, see Figure 2. Additionally, we deliver annually more electrical power than the heat pump and the auxiliary pumps need, see Table 5. This shows that also focusing on the active systems when refurbishing, has a great potential to transform energy guzzling buildings in zero or plus energy buildings without having to perform significant alterations to the building hull. By improving the controls to avoid auxiliary pumps running when no direct need or interesting gain can be reached, we expect to reduce the annual power consumption of the auxiliary pumps as well as the required heating power, thus further improving the sustainability of the active refurbishment strategy, since less PV-T will be required.

Costs

From a financial point of view, little upgrades to the façade in combination with an exergy-efficient system are most reasonable for the considered cases. Exchanging the glazing of the existing windows has already great leverage to increase the thermal resistance of the facade. Even apparently little additional upgrades to the envelope, like a better-insulated roof, have comparatively less effect compared to investing in glazing with higher thermal resistance. However, this result is currently distorted in real life projects by governmental subsidies that favour the installation of active or passive components.

We expect the cost of electricity per kWh to rise in

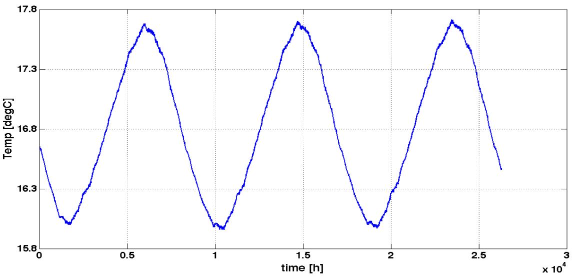


Figure 2: Average deep storage temperature plotted over three years

the future, due to the trend of reducing the conventional generated electricity by increasing the share of electricity generated with renewable resources. The current price of electricity per kWh generated free of emissions is 0.702 CHF in Zurich. This would favour the case DFH60.

Market Value

The installation of PV-T on the flat roof of DFH100-60-45 does not necessarily change the market value, if well integrated. The constraints of the DFH15 require the greatest changes to the existing design of the façade, which reduces the qulity of spaces facing North. Thus, we see potential to keep the market value of the heritage buildings and also becoming emission free in operation by refurbishing them similar to the DFH100-60-45, as no alterations to the original design of the façade are required.

Embedded and Operational Emissions

The cases with PV-T collector annually produce a surplus of electricity. This ensures an emission free operation for the cases DFH100-60-45. Eventhough the primary energy demand of the DFH15 is severly reduced, 0.154 kg CO_2-eq emissions need to be considered per kWh if the electricity is from the Swiss energy mix (Frischknecht, 2008).

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