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Energy refurbishment of historic districts: A techno-economic and environmental analysis of a case study

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Abstract

A techno-economic and environmental analysis of proposed energetic refurbishment measures combined with energy supply variants for a historic district in Switzerland (303 entities; 64’546 m^2 energy reference area (A_E)) is given. The economic evaluation is based on the Net Present Value (NPV) method and the environmental impact is quantified in “eco-points” (German: “Umweltbelastungspunkte” (UBP)) and equivalent CO_2 emissions. Data for the analysis is provided by the Swiss building certification (German: “Gebäudeenergieausweis der Kantone” (GEAK)) and secondary literature. A total of three variants, V I through V III is analysed.

The results show how current limit values for heating demand can be met with energetic refurbishment measures (including aerogel-super-insulation materials) which conform to requirements of the regional monument protection. It is found that a local heat distribution system based on a Brine/Water Heat Pump (B/W HP) (V I) can reduce the environmental impact for heating, hot water, ventilation, auxiliary energy (HWVA) from currently 1.8 tons CO_2 eq per capita and annum (p.c.a.) (1.5 Million UBP’s p.c.a.) for the fossil fuel based system to 118 kg CO_2 eq p.c.a. (325 thousand UBP’s p.c.a.). The environmental impact of a central wood chip plant (Combined heat and power (CHP)) in V II or a district heating based system in V III is slightly higher than in V I. Negative NPV (for a 30 years’ time frame) is found for all three mentioned energy supply systems in combination with energetic refurbishment measures (V I: -147.- CHF/m^2 A_E, V II: -125.- CHF/m^2 A_E, V III: -98.- CHF/m^2 A_E). However, it can be shown that reducing the energetic refurbishment costs by one third leads to a positive NPV for all three variants mentioned. Furthermore, the NPV-results do not differ significantly between the variants and should therefore not be the sole basis for decision-making.

A sensitivity analysis shows a great impact of materials’ lifetime on the NPV. Therefore, reliable estimates for e.g. aerogel-super-insulation materials are important data for a NPV evaluation. Furthermore, the environmental impact was calculated for HWVA, only. This system boundary should be extended to domestic electricity consumption, embodied energy in insulation materials and PV in further research.

Keywords: aerogel-super-insulation, historic district, energetic refurbishment, energy supply variants, sustainability assessment

Table 1: Nomenclature.

Q	energy [kWh/(m^2 A_E)]	V	ventilation losses
E	gross final energy consumption [kWh]	E	energy reference area
A	surface [m^2]	e	outside
SPF	Seasonal performance factor for HP systems	th	thermal
C	cash flow [CHF]	el	electrical
h	hour	int	internal
Greek letters		h	heating
	temperature [° C]	w	hot water
	required heating capacity [kW]	d	distribution losses

	Efficiency coefficient	y	year [1…Y]
Subscripts		i	entity [1…I]
me	yearly average	B/W	Brine / Water
T	transmission losses	A/W	Air / Water

1. Introduction

At the recent climate change conference in Paris, 195 states agreed on the reduction of anthropogenic greenhouse gas (GHG) emissions in order to limit global warming to maximal 2 K [1]. GHG reduction within the building sector plays an important role hereby, since 18.4 % of all anthropogenic GHG emissions world-wide are directly or indirectly caused by this sector [2]. In Switzerland, buildings even show a 40 % share of the total CO_2 emissions in the year 2015 [3]. Close to 20 % of Swiss residential buildings are historic and were built before 1920 [4]. Ca. 4 % are worthy of historic preservation [5]. Such buildings consume about four times more heating energy p.a. as newly built constructions [6]. Therefore, energetic refurbishment and a transition from fossil fuels to renewable sources to cover the energy demand of historic buildings are crucial to reach the climate goals.

One challenge in energetic refurbishment of historic constructions is to use insulation materials that do not alter the building characteristics. The efficiency measures for building envelopes also influence the optimal energy supply system, if technical, economic and environmental criteria are considered. Furthermore, the optimal energy concept may change if the scope is enlarged from one to several buildings in a historic district.

In this paper, energetic refurbishment measures and several energy supply systems are proposed for a historic district in Switzerland. The evaluation is primarily based on Swiss energy certificates (GEAK, German: “Gebäudeenergieausweis der Kantone”) of several buildings, yearly energy consumption data and data retrieved from secondary literature. The proposed systems are evaluated based on technical, environmental and economic criteria.

2. The Case Study

The historic district consists of 303 entities (263 single- and 40 multi-family houses) in architectonical styles of late Baroque, Romanesque-traditionalist and expressionism, being built between 1919 and 1927. The buildings are mainly owned by two owner cooperatives. The present energy reference area of the historic district is approximately 64’500 m^2.

Several energetic refurbishment measures have been implemented since 1990, mainly in single family houses (SFH), however. Insulation has been applied to the attic floor and the cellar ceiling. Furthermore, single-pane windows were replaced with windows featuring insulating glazing units. Some oil-fired heating system has been renewed in the SFH. The majority of multi-family houses (MFH) have gas heating installations.

2.1 Energetic refurbishment approach

The measures for energetic refurbishment considered are developed in close collaboration with the owner cooperatives and the regional monument protection authority. The main restraints are the prevention of a reduction of the living space and the preservation of the external appearance of the buildings. The energetic refurbishment measures deemed acceptable are summarized in Table 2.

Reinforcement of the insulation on the attic floor and the cellar ceiling are measures which do not include any penalty on living space available. Windows with triple glazing units are proposed. For the façades, a thin layer of aerogel based superinsulation is proposed as a compromise between energy efficiency and monument protection. Furthermore, a ventilation system with heat recovery is proposed.

Aerogel based insulation materials are characterised by a low thermal conductivity. This is attributed to a combination of low density and porous material with a micro meter pore size. These so called “super insulation materials" are commonly applied for the renovation of historic buildings due to a reasonable thermal resistance with relatively thin layers. Current studies present low values for embodied energy and net lifetime environmental impact (a calculation which combines indirect and direct impact factors) of aerogel based insulation materials compared to alternative materials [7,8]. In the project, an aerogel insulation system was considered which has been tested in practice and is an appropriate façade retrofit of historic buildings [9].

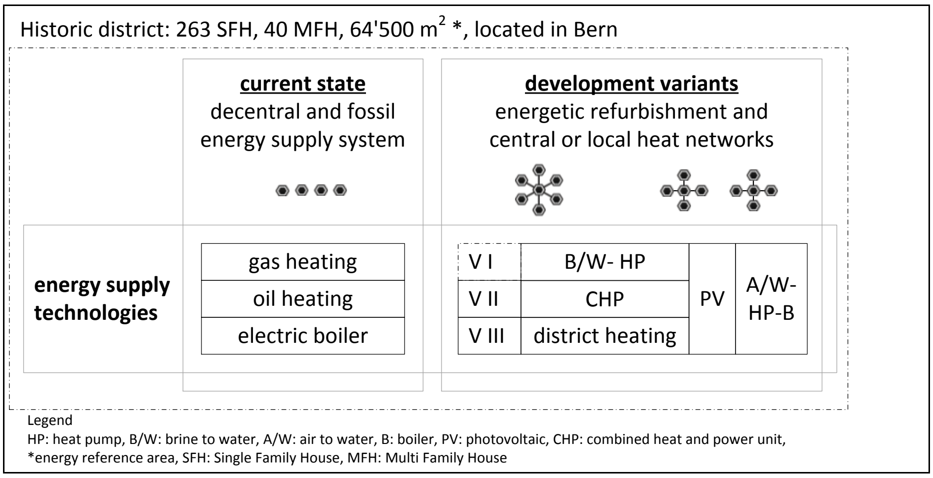
Table 2: Energetic refurbishment measures.

Construction	**Energetic refurbishment measures**	**Weighted average U-Value [W/(m^{2}K)]**	
		Current state	**Applied measures**
Façade	Aerogel insulation board (4 cm), λ = 0.017 W/(m K)	1.10	0.32
Windows	Wood-metal frame with triple glazing units U_f 1.2 W/(m^2 K), U_g 0.5 W/(m^2 K), ψ_g 0.04 W/(m K)	1.68	1.09
Attic floor	8 cm wood fibre insulation λ = 0.05 W/(m K)	0.45	0.17
Ground floor		0.68	0.28
Ventilation	Ventilation system 70 % heat recovery	-	-

2.2 Energy supply system

The current heating energy supply in the historic district is based on fossil fuels. Three development variants are considered for the techno-economic and environmental evaluation of future heating energy supply – and domestic hot water – systems (see Figure 1).

The system boundary is depicted in Figure 1. The energy balance of the district includes heating, hot water, ventilation, auxiliary energy (HWVA). Furthermore, for all variants a central low temperature heat distribution network is included. The same system boundary is used for both the economic and ecological analysis. Other fields of energy consumption, such as appliances, lighting, mobility and embodied energy of building materials and the energy supply infrastructure are outside of the system boundary.



Legend
HP: heat pump, B/W: brine to water, A/W: air to water, B: boiler, PV: photovoltaic, CHP: combined heat and power unit,
*energy reference area, SFH: Single Family House, MFH: Multi Family House

Figure 1: System boundary and development variants of energy supply technologies.

3. Method

3.1 Energy consumption and supply

In order to estimate the current gross final energy consumption of the district, two data sources are used. For the subset of the buildings, for which consumption data is available, this data is adjusted by using heating degree days. For a selection of the buildings for which energy consumption data is not available, gross final energy demand is calculated with the GEAK-tool and then aggregated for the entire subset. Heat demand for these buildings is thus based on SIA standard 380/1:2009 [10]. The final energy demand considering energetic refurbishments (see

Table 2) is also calculated with the GEAK-tool. Mainly corner buildings are selected for evaluation in order to have a conservative (high) estimate of energy demand. For the same reason, the GEAK-tool results are used for energy demand after energetic refurbishment.

On average, the data on energy consumption (heating degree days adjusted and averaged for the past five years) is 35 % below the demand results obtained by the GEAK-tool. To be on the safe side in cost and demand estimates, all variant calculations are based on the demand values. Calculations for the reference case “fossil” are based on consumption data wherever possible.

For the B/W HP heat supply system variant, the district’s gross final energy demand for year y is calculated according to eqn. (1). Q_d is the energy loss within the heat distribution network. The seasonal performance factor (SPF) is calculated with the building simulation software Polysun [11]. The calculation is based on building characteristics of a district’s typical entity in a refurbished state. Therefore, the inlet temperature of radiators corresponds to a low-temperature heat system.

$$_{h,I,y} = \frac{\sum_{i=1}^{I} Q_{h,i,y} \cdot A_{E,i} + Q_d}{SPF_{B/W}} \qquad \text{[kWh]} \qquad (1)$$

The central CHP plant generates heat and electricity. In the gross final thermal energy calculation an overall efficiency coefficient (η) of the furnace and the fraction (η_{th}) of heat is considered acc. to eqn. (2). The electricity generated is derived by the multiplication of $\mathrm{E}_{h,I,y}$ by η_{el}.

$$_{h,I,y} = \frac{\sum_{i=1}^{I} Q_{h,i,y} \cdot A_{E,i} + Q_d}{\eta \cdot \eta_{th}} \qquad \text{[kWh]} \qquad (2)$$

The gross final thermal energy of the district heating variant is calculated as depicted in eqn. (3).

$$_{h,I,y} = \sum_{i=1}^{I} Q_{h,i,y} \cdot A_{E,i} + Q_d \qquad \text{[kWh]} \qquad (3)$$

The gross final thermal energy consumption for domestic hot water production is calculated acc. to eqn. (4).

$$_{w,I,y} = \frac{\sum_{i=1}^{I} Q_{w,i,y} \cdot A_{E,i}}{SPF_{A/W}} \qquad \text{[kWh]} \qquad (4)$$

The annual electricity yield from the photovoltaic (PV) panels is calculated with the building simulation software Polysun [11].

3.2 Required heating capacity

The required heating capacity is calculated acc. to eqn. (5). This calculation is based on [12]. $_e$ corresponds to the lowest daily average temperature of the past 20 years.

$$\Phi_{h,I,y} = \frac{\sum_{i=1}^{I} \left(Q_{T,i,y} + Q_{V,i,y}\right) \cdot A_{E,i}}{8760\ h} \cdot \frac{_{int} - \ _{e}}{_{int} - \ _{me}} \qquad \text{[kW]} \qquad (5)$$

For domestic hot water, an additional required heating capacity is calculated based on [13] acc. to eqn. (6).

$$\Phi_{w,I,y} = \frac{\sum_{i=1}^{I} Q_{w,i,y} \cdot A_{E,i}}{8760\ h} \qquad \text{[kW]} \qquad (6)$$

3.3 Environmental impact

The assessment of the environmental impact is based on the gross final energy demand (3.1) and is evaluated by two different criteria.

Firstly, the equivalent CO_2 emission is calculated. The CO_2 eq. allows a comparison of the districts average environmental impact – before and after the energetic refurbishment measures have been applied – to the state of the art of energy efficient buildings. Furthermore, the results can be interpreted in regard to the goals of a 2’000 Watt society [14]. Secondly, “eco-points” (German: “Umweltbelastungspunkte” (UBP)) are derived from the final energy consumption. In an analysis of UBP’s, besides the primary energy ten more criteria are considered and weighted by the Swiss environmental policy objectives [15].

3.4 Economic analysis

The NPV of the energy supply and energetic refurbishment variants represents the sum of discounted net cash flows within the time frame investigated minus the total initial investments acc. to eqn. (7). The NPV of the proposed energy supply variants is calculated in comparison to the renewal of the current fossil fuel based system without energetic refurbishment.

$$\mathrm{NPV_Y} = -\mathrm{C}_0 + \sum_{\mathrm{y}=1}^{\mathrm{Y}} \frac{\mathrm{C}_y}{(1+\mathrm{r})^y} \qquad \text{[CHF]} \qquad (7)$$

The internal rate of return (IRR) signifies the discount rate r for which the NPV acc. to eqn. (7) equals zero after a 30 years’ time frame investigated. The payback period (PBP) is defined by the year in which the sum of cash flows in eqn. **Error! Reference source not found.**(7) exceeds initial investment, given that $\mathrm{r} = 0$.

Positive cash flows are financial contributions for energetic refurbishment measures and drawbacks from generated electricity by PV or CHP. Negative cash flows are initial investments in energetic refurbishment measures, in energy supply technologies (see Figure 1) and in heat distribution networks. Furthermore, net present operating costs and Net Present Energy Costs (NPEC) are considered for all variants. Energy costs in V III are based on the energy consumption plus the connected load which is scaled up acc. to the required heating capacity.

The initial investments in energy supply technologies as well as operating costs for system maintenance of all variants are scaled according to the required heating capacity or kW_p power of the PV. In all variants, costs for A/W HP domestic hot water (DHW) boilers are split into initial investments per entity (e.g. installation, planning etc.) and expenses which increase linearly with the required heating capacity. In the fossil based reference variant, costs are estimated for SFH and MFH and scaled up accordingly. The expenses for a district heating network within the district are calculated for an estimated overall pipe length.

Only cash flows within the time frame investigated are considered. An initial investment or drawbacks from the support scheme for constructions with a lifetime which exceeds this period are adjusted accordingly. Reinvestments are considered for constructions with a lifetime below the time frame investigated.

Two scenarios in regard to the energy price development during the time frame investigated are considered. The scenarios are based on the price trend, estimated within the Swiss Energy Strategy 2050 [16,17]. Furthermore, current subsidies for electricity generated by CHP or PV installations are considered in the calculation of positive cash flows. The Swiss feed-in tariff is paid out for a limited time frame only [18]. After this period, generated electricity is either used within the district or fed into the power grid at market price.

4. Input parameters

4.1 Energy demand

District energy consumption data of several entities is available for 2011-2015. Final energy demand for heating is calculated based on 10 energy certificates for different building types of the district as described above. An additional energy demand for hot water (Q_h) of 75 MJ/m^2 A_E for MFH and 50 MJ/m^2 A_E for SFH is considered, respectively [10]. The required heating capacity is calculated with a 20 °C inside temp. (θ_{int}), -7 °C lowest daily average outside temp. of the past 20 years (θ_e) and the average yearly outside temp. (θ_{me}) of 9.1 °C (acc. to the weather station in Bern) [19,20].

The calculated $SPF_{B/W}$ factor for the energy supply system with B/W HP is 3.8. An analysis of current B/W HP shows on average a coefficient of performance of 4.7 (linear regression with n: 548 and a p-value < 1 %), given a 35 °C water temperature (limit value of floor heating systems acc. to [21]), a brine temperature of 10 °C and 4 % losses for pressure drops in the evaporator [13,22]. Therefore, the SPF considered is a conservative estimate. A $SPF_{A/W}$ factor of 3.3 is considered for the A/W HP DHW boilers. This value is in agreement with the target value of current standards [23].

An overall efficiency factor of 80 % is considered for the wood chip plant. Based on this, the share of thermal energy $_{th}$ is 61 % and the fraction of electricity is 39 %. These parameters correspond to operating data of CHP plants in the Zürich region (Aubrugg) [24].

Heat distribution losses of 0.3 W/(m K) are included in the energy demand calculation. For the energy distribution losses Q_d in Wh this value is multiplied by the estimated lengths of the district heating network (5’000 meters), the temperature difference (30 K) and the estimated full load hours per year (1850 hours).

The annual electricity generation by the PV-panels amounts to approx. 500 MWh (490 kW_p ; azimuth: 0°; 30° tilt angle; location: Bern). It is assumed that 3’800 m^2 can be made available for PV on the roof of new buildings around and/or within the historic district.

4.2 Environmental impact

Acc. to [25] an environmental impact of 61 UBP/MJ oil fuel, 38 UBP/MJ natural gas, 25 UBP/MJ wood fired in a central wood plant and 106 UBP/MJ electricity from power outlets occurs. The environmental impact of district heat amounts to 37 UBP/MJ and is calculated based on an 18 % share of a waste incineration, 30 % wood and 52 % gas [25]. The share is based on the heating capacity of a district heat plant in Bern [26].

4.3 Economic analysis

Initial investments and operational costs (4'300 CHF/kW) for the B/W HP system (V I) are based on average costs of two comparable projects [27,28]. The investments for the CHP (2'200 CHF/kW) correspond to the average costs of eight comparable projects [29–35]. Operational costs are based on [31,36] and corr. to 50 CHF/kW p.a. for the B/W HP system and 380 CHF/kW p.a. for the CHP, 730 CHF/house for the oil-fired heating and 530 CHF CHF/house for the gas-fired heating. Investments for A/W HP DHW boilers per installation (7’650 CHF/house) and per kW heating capacity (500 CHF/kW) are calculated based on 9 currently available models [37]. The fossil fuel system costs (av. Value: gas ≈ 43’100 CHF/house, oil ≈ 24’500 CHF/house) are based on [36]. The costs for energetic refurbishment are evaluated by the GEAK experts for every building type (av. value: 180’000 CHF/house incl. ventilation system). The costs for the energy distribution network (850’000 CHF/km) within the historic district are calculated based on two reference projects [29,31]. The estimate for initial costs of the PV installation (1’800 CHF/kW_p) is based on the average value of two studies [38,39]. The operational costs (30 CHF/kW_p) are based on results of a survey which was conducted in Switzerland (2014-2015 n: 247) [40].

The electricity price (20.8 Rp./kWh) for the reference year 2015 is based on a market average (after taxes, for households consumption profile H4: 4’500 kWh p.a.) [41]. The price (5.4 Rp./kWh) of wood chips corresponds to an estimate for the Swiss market 2015/16 [42]. The oil-, gas- and district heat- energy price is based on [43] (7.3, 7.8, 6.8 Rp./kWh, respectively). An additional price per connected load is considered for district heat energy (35.25 CHF/kW p.a.) [44]. The price development p.a. corresponds to an average of two Swiss energy market scenarios (electricity: 1.4 % p.a., wood: 2.2 % p.a., oil: 2.4 % p.a., gas: 1.4 % p.a., district heat: 1.7 % p.a.) [16].

The current federal and cantonal subsidies scheme is considered for the energetic refurbishment (on average 47 CHF per m^2 A_E). For the electricity generated by PV or the wood chip CHP plant a feed-in tariff of 15.6 Rp./kWh and 30.8 Rp./kWh, respectively, is included in the calculation for a 20 year period [18]. After 20 years, a feed-in tariff of 7.6 Rp./kWh is considered for PV (after a 50 % self-consumption-rate) [45]. For the wood chip plant a 100 % self-consumption rate is assumed.

The lifetime of the energetic refurbishment measures and energy supply systems is partially based on a leaflet by the SIA [46]. Therefore, a lifetime of 30 years is assumed for PV installations and the ventilation system. The A/W HP DHW boilers have an expected lifetime of 20 years. A lifetime of 50 years is assumed for the energetic refurbishment measures. This value is based on [47,48] and refers to the aerogel insulation. The energy distribution network is assumed to last 60 years. A lifetime of 40 years is considered for the CHP plant and the B/W HP system. The average lifetime of the fossil fuel systems is 27 years [36].

A typical discount rate (2 %) for low risk projects in the construction sector is considered [48].

5. Results

The results show that the energetic refurbishment measures proposed considerably reduce energy costs and the environmental impact of the heat supply. However, none of the energy supply variants considered shows a positive NPV over a 30 year time span.

The current yearly weighted-mean heating energy demand of the historic district exceeds the limit value for new buildings by more than 2.5 times and the limit for refurbishments by 2 times (Figure 2) [10]. Energetic refurbishments (see 2.1) reduce the energy demand for heating by approx. 70 %. In this case, the limit values for new constructions energetic refurbishment and for refurbishments are undercut by approx. 20 % and 40 %, respectively.

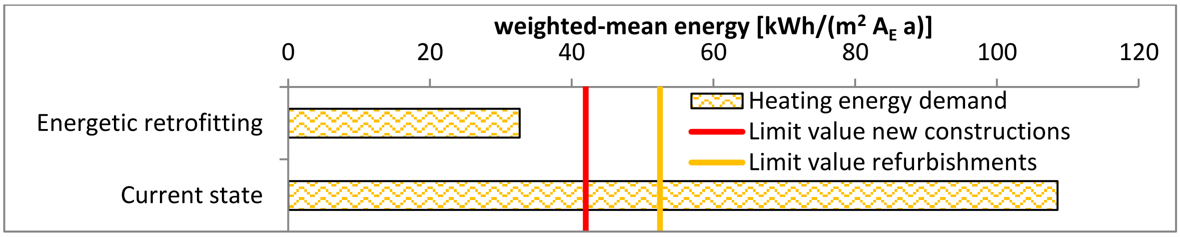


Figure 2 Heating energy demand p.a. (weighted-mean by A_E) for current state and after energetic refurbishment.

The yearly NPEC for energy of all three variants reflects the reduction in the heating demand (see Figure 3). Furthermore, the B/W HP variant (V I) shows the lowest yearly NPEC compared either to the wood chip CHP plant (V II) or the connection to a regional district heating system (V III). The energy mix of V I is fully based on electricity. Variant II includes a large share of wood and V III a share of district heat as energy source (Figure 3). The reference variant shows a heavy dependency on fossil fuels (i.e. oil and gas).

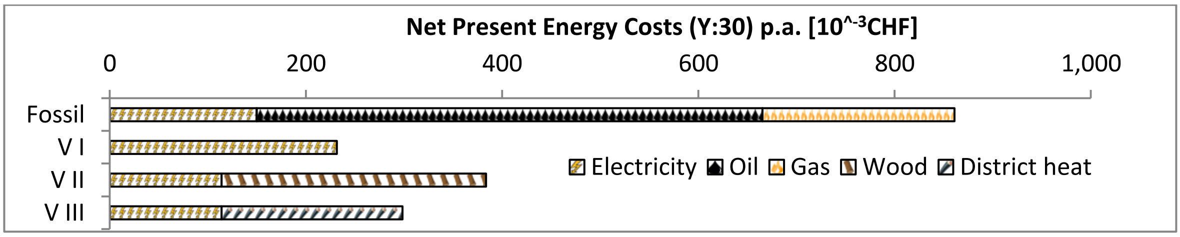


Figure 3 Fossil ref. and energy supply variants: yearly NPEC (Y:30) and energy mix of the district.

As can be seen in Figure 4 a renewal of the fossil fuel system without energetic refurbishments shows the lowest Net Present Capital Costs (NPCC). Furthermore, NPCC of all three variants are quite close together. Variant III results in the lowest NPCC. Variant II and Variant I follow with an increase of approximately 5 to 9 % respectively for the 30 year time span considered. However, the highest NPCC only for the energy supply system are observed for the fossil fuel reference variant. Due to a relatively long lifetime of 40 and 60 years, respectively the heating supply system in V I and V II and the heat distribution network show comparatively low NPCC values.

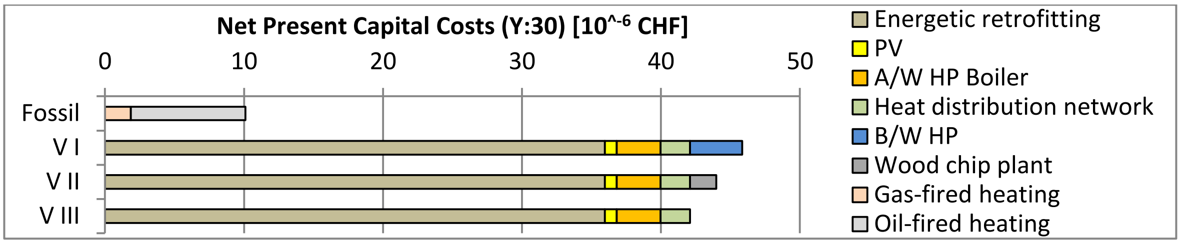


Figure 4 NPCC (Y:30): Fossil reference and for energy supply variants.

The economic analysis shows a negative NPV for all three variants. For V I a NPV of -147.- CHF/(m^2 A_E) is found, for V II and V III NPVs of -125.- CHF/(m^2 A_E) and -98.- CHF/(m^2 A_E) are found, respectively. Both the Internal Rate of Return (IRR) and Payback Period (PBP) within the time frame investigated is negative for V I. The IRR is found to be 0.2 % for V II and 0.5 % for V III. The PBP's found for V II and V III are 30 years and 28 years, respectively. Variant II shows the highest operational costs compared to V I and V III (see Figure 5). However, the net present profits in V II are also higher than in V I and V III and thus compensate for the expenses during operation.

The environmental impact p.a. for HWVA can be reduced tremendously in the energy supply variants compared to the reference fossil fuel energy system (Figure 5). In the fossil fuel reference variant the environmental impact measured in UBP's amounts to approx. 1.5 million points per resident and year (p.c.a.) (≈ 1.8 t CO_2 eq p.c.a.). This can be reduced to 325 thousand UBP's (p.c.a.) in V I (118 kg CO_2 eq p.c.a.), 400 thousand UBP's p.c.a. in V II (94 kg CO_2 eq p.c.a.) and a comparable 380 thousand UBP's p.c.a. in V III. However, in V III the equivalent CO_2-emissions are quite a bit higher than in V II (350 kg CO_2 eq p.c.a.). It should be noted that electricity generated by PV and CHP is not considered in the quantification of the environmental impact.

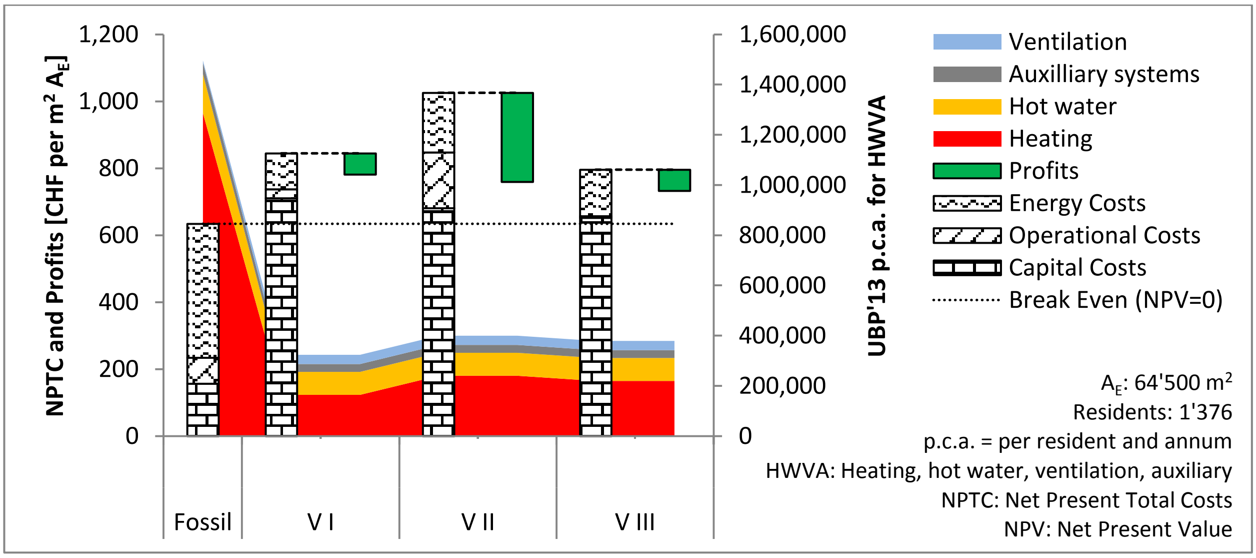


Figure 5 NPTC, profits (Y:30) and UBP's p.c.a. for fossil ref. system and the energy supply variants.

In the sensitivity analysis a set of parameters is changed by plus and minus 1/3. The percentage change of the NPV is demonstrated in Figure 6. Results show that V I is generally least affected by a parameter change. Furthermore, the lifetime and the energetic refurbishment are parameters with large impact on the NPV.

If energy costs increase by 1/3 compared to the base value, an increase of the NPV can be observed for all energy supply variants (Figure 6). The NPV for V III increases the most and actually becomes greater than zero for this example. The positive impact of energy cost on the NPV is due to the high base cost for fossil fuel which makes alternative energy variants financially more attractive.

A reduction in initial capital costs unsurprisingly improves the NPV for all energy supply variants. An approximate equal effect on the NPV can be observed for all energy supply variants. It is assumed that the costs of renewal for the fossil system are not very sensitive to changes. Therefore, these base values remain unchanged in this comparison.

The NPV for all energy supply variants is positive if costs for energetic refurbishment decrease by 1/3 of the base values assumed (IRR: V I 2.5 %, V II: 3 %, V III 3.6 % and PBP: V I: 21 years, V II, V III: 19 years). The impact of a change in the costs of energetic refurbishment is inverse to the change direction and most strong for V III. This is attributable to the cost structure. The energetic refurbishment accounts for approx. 85 % of all NPCC in V III. In V I, this share is approx. 7 % smaller. Therefore, a change in the costs of energetic refurbishment measures alters NPV most strongly in V III.

The NPV of V I and V II is negatively influenced by a +1/3 change in operational costs. A contrary impact is observed for V III.

The strongest impact on the NPV is observed by a reduction of the expected useful life of the energetic refurbishment measures and energy supply systems. A 33 % increase in the expected useful life leads to a positive NPV for all variants (IRR: V I, V II, V III: 3 %, PBP: V I: 22 years, V II: 21 years, V III: 20 years).

The NPV of all energy supply variants increases if the discount rate is reduced by 1/3. The NPV is altered asymmetrically, whereas the positive effect of a decrease in the discount rate is larger than the negative effect of an increase.

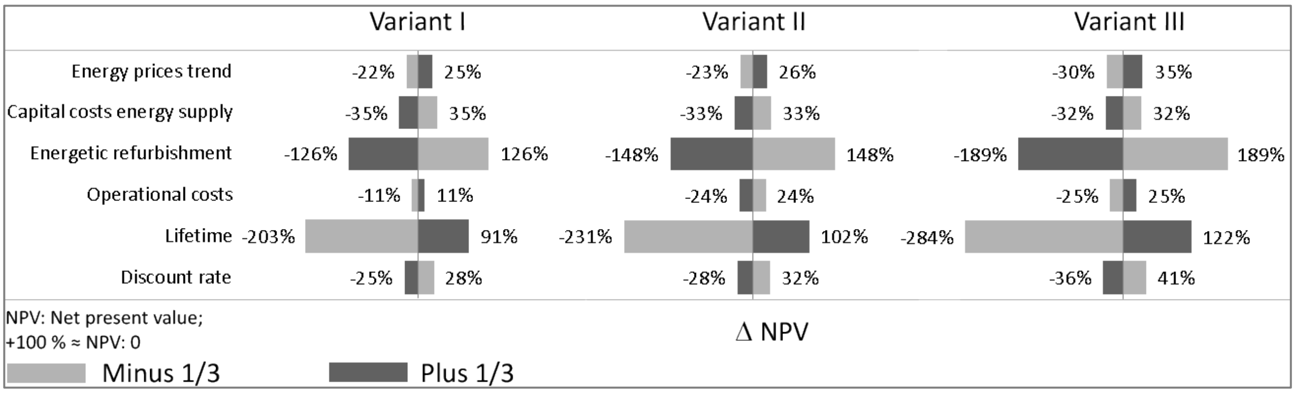


Figure 6 Sensitivity analysis of selected parameters on the NPV of the studied energy supply variants.

6. Discussion

Three energy supply variants demonstrate alternatives to a fossil fuel based energy system. A B/W HP variant (V I) transforms the fossil fuel based reference system into an electricity based system with low energy costs. The cost advantage can be attributed to the usage of environmental heat which is less costly in comparison to wood or district heat. Results of the sensitivity analysis confirm that environmental heat source based systems can reduce risks associated with the development of energy prices. Furthermore, the electricity based energy system offers more flexibility in the choice of energy source. E.g. the share of electricity generated within the district can be enlarged or the environmental impact of electricity drawn from the power grid can be reduced by ordering certified products. However, the environmental impact in V I, measured per resident, is already low if the average Swiss grid electricity is considered. A comparison to the total average environmental impact, measured in UBP's, per person and year in Switzerland [49], in the current state a 7.5 % share results only for HWVA (1.5 Million UBP's p.c.a.). This can be reduced to 1.6 % (325 thousand UBP's) in V I. If quantified in CO_2 eq p.c.a., energetic refurbishment and the energy supply system in V I reduces current states' environmental impact of 1.8 tons CO_2 eq p.c.a. to 0.12 tons p.c.a. (the threshold value for a 2000 Watt society equals 1 ton CO_2 eq p.c.a. and current average in Switzerland is 7.2 tons CO_2 eq p.c.a. ; see [14]). This corresponds to an absolute reduction of 2'500 tons CO_2 eq. p.a. for the district considered. Comparatively high capital costs and a low NPV (Y:30) (- 9.5 Million CHF) can be identified as quite serious disadvantages in V I.

A CHP based heating system (V II) generates electricity besides thermal energy which is an important income due to a feed-in tariff for electricity generated by a CHP plant which is nearly twice as high as for PV (NPV (Y:30): - 8 Million CHF). However, the consumption of wood, necessary to cover the heating demand, implies a relatively high environmental impact when expressed in UPB's. In addition, an increase in environmental regulations can be expected for CHP plants situated in urban areas [50]. Another disadvantage can be identified in the expected considerable price increase of wood chips as energy source. So, even though district heating is currently more expensive than heating by wood chips, the expected price increase at a higher pace will turn this around in the near future [16,43,44].

The district heat system (V III) shows best results regarding NPV (Y: 30) (-6.3 Million CHF), PBP and IRR. Furthermore, V III has an advantage in regard to capital costs. However, energy costs and environmental impact is largely dependent on the energy distributors' offer.

The sensitivity analysis shows that costs for energetic refurbishment and costs attributable to the expected useful lifetime of system components are the most relevant factors for a profitable investment. The largest costs of energetic refurbishment are attributable to aerogel insulation material installations on the building envelope. It is expected, however, that the price of insulation materials based on the aerogel technology is going to drop considerably in the near future due to the economics of scale and technological advancement [8,9,51]. Available literature on the expected lifetime of aerogel based insulation materials is scarce. However, the assumption of 50 years lifetime is probably an optimistic estimate and no dramatic positive changes in this value can be expected (see [47]). A reduction in costs for energetic refurbishment (excl. ventilation system) by approx. 35 % would lead to break-even (NPV = 0).

7. Conclusion

A techno-economic and environmental analysis of energetic refurbishment and three energy supply variants combined with a local heating distribution network for a historic district is described in this paper. The economic calculations are based on the NPV method (Y:30) and the environmental impact is quantified with UBP's and CO_2 eq. The energy demand of the buildings is based on GEAK certificates, which were prepared for exemplary buildings within the district. Also, consumption data for a part of the buildings was available.

The results show that energy savings can cover a large fraction of NPC for the energetic refurbishment and energy supply variants compared to the reference fossil fuel system. However, break-even cannot be achieved for any of the variants considered. Possible solutions for a profitable investment are a reduction in the energetic refurbishment costs or additional financial contributions from federal or cantonal level.

A comparison of the energy supply variants shows a relatively small difference in the results of the NPV-analysis. However, the B/W HP energy supply system (V I) offers most flexibility (in terms of energy source), lowest risks which are attributable to a possible energy price increase and smallest environmental impact. A central CHP plant (V II) generates highest profits due to the feed-in of electricity generated into the power grid. The NPV exceeds that of V I by 20 %. A connection to a district heating system (V III) shows the best results in the NPV-analysis. However, V II and V III are dependent either on a specific energy source or on the offer of a local energy distributor. This dependency is subject to risks associated with price development or future regulations.

The results shown herein will contribute to building cooperatives or real estate companies' decision process on how to develop sustainable energetic refurbishment and energy supply systems. Furthermore, the findings demonstrate the important role of policy makers in implementing affordable sustainable energetic refurbishment and energy supply systems for historic districts.

Further research in regard to the expected lifetime of super insulation materials is necessary, as this has a large influence on the economic performance of energetic refurbishment projects. Furthermore, the environmental analysis in this research is restricted to HWAV. This system boundary should be broadened to include electricity consumption of household appliances and embodied energy of insulation materials and PV.

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