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INTEGRATED STRATEGIES AND POLICY INSTRUMENTS FOR RETROFITTING BUILDINGS TO REDUCE PRIMARY ENERGY USE AND GHG EMISSIONS (INSPIRE)

GENERIC STRATEGIES FOR BUILDINGS IN SWITZERLAND

SWISS CONTRIBUTION TO THE ERA-NET « ERACOBUILD »

Final Report

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Table of contents

Vorwort

Seit Mitte der 1970er Jahre arbeiteten Fachleute, Verbände und Behörden in der Schweiz und in Europa an der Verbesserung der Energieeffizienz im Gebäudebereich, um zunächst die Abhängigkeit von fossilen Energieträgern und in der Folge den Ausstoss von CO_2-Emissionen zu reduzieren. Entsprechend konzentrierten sich die Anstrengungen während langer Zeit auf den thermischen Energiebedarf für Raumwärme und Warmwas-ser (SIA 380/1). Mit dem Aufkommen und der verstärkten Diffundieren der Wärmepum-pentechnologie seit den frühen 1990er-Jahren, dem steigenden Stromverbrauch von Nicht-Wohngebäuden und des Einbezugs von weiteren Umweltkriterien im Kontext von Lebenszyklusanalysen wurde der Fokus auf die Aspekte Strom (siehe z.B. SIA 380/4) und Primärenergie (2000-Watt-Gesellschaft, SIA Effizienzpfad) erweitert.

In Bezug auf die Bewertung von Massnahmen im Gebäudebereich hat sich hierdurch eine zusätzliche Komplexität bei der Wirkungsbeurteilung ergeben. Die beiden Kriterien Treibhausgase und Primärenergieverbrauch eignen sich, diese Komplexität zu reduzieren und die Vergleichbarkeit der Wirkung und der Kosteneffizienz von verschiedenen Massnahmentypen sicherzustellen. Aus Sicht von Gebäudeeigentümern ist es in der Tat zentral, Erneuerungsstrategien mit kostenoptimalen Lösungen und möglichst grossen Zielbeiträgen zu identifizieren. Das Projekt INSPIRE, namentlich der vorliegende Projektbericht und das entwickelte und hier angewandte INSPIRE Tool leisten einen Beitrag hierzu.

Dieser Projektbericht und das INSPIRE Tool nehmen explizit den individuellen Standpunkt von einzelnen Gebäudeeigentümern und Portfoliobewirtschaftern ein. Die gewonnen Erkenntnisse, gezogenen Schlussfolgerungen und Empfehlungen gelten aus dieser einzelwirtschaftlichen Perspektive. Diese können zum Teil, aber nicht unbesehen auf die gesamtwirtschaftliche Ebene übertragen werden.

Aus einer gesamtschweizerischen oder gar europäischen Optik sind weitere Aspekte mit zu berücksichtigen. Dazu gehören namentlich Systemüberlegungen, vor allem im Bereich der leitungsgebundenen Energieträger. Sowie Potenzialbeschränkungen. Beispielsweise sind zertifizierte erneuerbare Wasserkraft, Biomasse oder CO_2-arme Fernwärme nur beschränkt verfügbar. Solche übergeordneten Überlegungen können und sollen durch die Anwendenden des INPIRE Tools im Speziellen und die Verantwortlichen im Gebäudebereich im Allgemeinen in ihren Entscheidungen mit einbezogen werden.

Summary

This report was established in the context of the project INPSIRE[1] which is an international project in the framework of ERACOBUILD. The report is one of the deliverables of the Swiss contribution to INSPIRE which consists of the assessment and evaluation of different retrofit strategies of buildings in Switzerland. The goal and scope of the Swiss part, which has been supported by different stakeholders from the sustainable construction sector in Switzerland (see impressum), are extended in relation to the international part of the project.

The building sector accounts for a large share of global final energy consumption in Switzerland. While energy related requirements for new buildings are constantly increasing, the improvement of energy performance of the building stock constitutes a major challenge for the future. The mastering of this challenge requires the identification of cost optimal retrofit strategies to achieve a targeted reduction of energy consumption and carbon emissions within building renovation. In this report such generic retrofit strategies are identified, assessed and compared for a representative type of multifamily house in Switzerland.

For this purpose, the INSPIRE tool was developed and applied, of which development constitutes another important contribution to the INSPIRE project. With the tool, environmental and economic indicators for buildings, greenhouse gas mitigation and primary energy efficiency strategies can be calculated.

The INSPIRE tool was developed to assess the impacts, trade-offs and synergies between different types of measures and to identify strategies aiming at reducing cost-effectively primary energy use and greenhouse gas emissions. The tool includes a database with empirical techno-economic characteristics for energy related retrofit measures, which can be categorized in seven strategic starting points: (i) building envelope insulation, (ii) efficient and renewable energy heating systems, (iii) ventilation system with heat recovery, (iv) efficient electricity based services (lighting, cooling, and appliances), (v) primary energy efficient and low GHG emissions intensive energy supply mix, (vi) building automation control and regulation, and (vii) onsite renewable energy generation and use, (viii) construction design and material choice with low embodied PE and GHG emissions. For two reference cases and up to eight renovation packages of measures, economic and environmental indicators may be calculated: investment costs and yearly costs, assuming a life cycle costing approach, total and non-renewable primary energy consumption, and greenhouse gas emissions. Using up-to-date empirical cost and price data the economic effectiveness and economic viability of the measures are assessed from a yearly-costs point of view, thereby assuming a private cost perspective, but not taking into account subsidies. With the tool the impact of factors such as starting situation, scope and costs of measures, interest rate and energy price expectations can be revealed.

[1] INSPIRE: Integrated strategies and policy instruments for retrofitting buildings to reduce primary energy use and GHG emissions

Research questions

The goal of the techno-economic assessment of energy-efficient building retrofit strategies in this study is to systematically address the following research questions:

- Regarding resulting costs, GHG emissions and primary energy (PE) use, what is the contribution of retrofit measures improving the energy performance of the building envelope in comparison to the use of renewable energies?
- Accordingly, what is the relation of building retrofit measures mentioned above as compared to options in the fields of efficient building technology, lighting and appliances?
- What is the impact on the results if embodied energy ("construction" according to SIA 2040) and related emissions are taken into account?
- To which extent are the findings affected if further options such as on-site energy production or the purchase of final energy with low carbon and PE content would be included in the set of options?
- What conclusions can be drawn based on these results and which recommendations can be made for building owners and investors?

Methodology

The report focuses on residential buildings without cooling needs. The methodology applied does not account for building related mobility nor for co-benefits of retrofit measures. The methodology includes embodied energy use and embodied GHG emissions (primary energy and GHG emissions content of retrofit materials and of construction), up-stream life cycle primary energy use for energy carriers and related greenhouse gas emissions.

The evaluation methodology is structured into the following steps:

Step 1: Definition of basic parameters: Future development of interest rate and energy prices; time period of the evaluation; electricity mix (Chapter 2.2)

Step 2: Selection of buildings for case studies (Chapter 2.3)

Step 3: Gathering of techno-economic data regarding primary energy and GHG mitigation measures (Chapter 2.4).

Step 4: Definition of the reference situation and of different strategies with corresponding measures to reduce primary energy use or GHG emissions, this for different types (retrofit strategies) of building owners (Chapter 3)

Step 5: Calculation of energy related impacts of the retrofit measures applied (methodology, see Chapter 2.1 and 2.4)

Step 6: Calculations of cost-effectiveness, i.e. of impact on GHG emissions, PE use and life-cycle-costs of different measures, this for various strategies (Chapter 3)

Step 7: Comparison of different (retrofit) measures and strategies (packages of measures) and conclusions concerning cost efficient and sustainable mixes of measures on the building envelope, the heating system and energy related building equipment (chapter 3.7)

Step 8: Recommendations for building owners and investors (Chapter 4).

The first, second and third steps are described more detailed in Chapter 2. The basic parameters of the calculations, such as energy prices, discount and interest rates, emission and primary energy factors, and climate data, are defined and presented in Chapter 2.2.

For the calculations a reference building is selected based on the Swiss building typology. The main focus of this report is on multi-family houses of different construction periods. According to the building statistics of the Federal Statistical Office (FSO) concerning the year 2000 fossil based heating systems used to be most common. Other heating systems are taken into account within the retrofit strategies.

The techno-economic data is related to construction, building retrofit and building technology measures used to mitigate GHG emissions and PE use. The data is gathered from different sources, such as “Elementartenkosten (EAK)” of the CRB (building envelope), Fernwärme Zürich and Amstein+Walthert (heating systems) and Siemens (building automation). The used techno-economic data is presented in Chapter 2.4.

In order to display the variety of different types of building owners and their individual preferences, four different types of owner dependent strategies were defined:

I. Investment scrooge

II. Environment-focused

III. Technology-focused

IV. Life-cycle cost-optimality (LCC optimality)

Each strategy type includes additional variants in order to take into account the sensitivity of different measures. The detailed strategy calculations and results are presented in Chapter 3. The detailed results for each of the main strategies applied to the reference situation are summarized and compared in Chapter 3.7. Additionally, the marginal costs and benefits of each measure as a function of GHG mitigation and PE efficiency increase are presented for the different strategies.

Results

As compared to the Reference 2 most of the strategies show for the first steps of the strategy a slightly increasing trend in terms of the costs as a function of decreasing GHG emissions and primary energy use. A slightly increasing curve as a function of **lower** GHG emissions and PE use (i.e. from the right to the left in Figure 1 and Figure 2) means that the measures are relatively cost-effective, albeit only nearly economically viable. Economically viable measures are characterized by decreasing curves. Yet most of the strategies yield a steep increase of the impact/cost-curves in terms of the last steps within a given strategy.

The different main strategies calculated in this report are presented in Table 1. Figure 1 and Figure 2 present the yearly costs as a function of GHG mitigation and PE use reduction of each main strategy. Remarkably, two of the strategies clearly reach the SIA 2040 guide values for residential buildings and GHG emissions (6 $kgCO_{2eq}/m^2a$ for operation), two strategies very scarcely and three further strategies only approximately. Three strategies reach the guide value for total PE use (450 MJ/m^2a for operation):

- Almost all strategies substantially reduce GHG emissions, mostly be more than 70%. An exception is the “Investment scrooge” strategy in which only about 50% of the maximum reduction is reached because it is less comprehensive in terms of potential measures. The guide value of SIA 2040 is reached in the four strategies Image oriented, GHG oriented, LCC optimal GHG oriented and LCC optimal GHG and PE oriented. The three last strategies are strongly going towards the guide value but do not reach it.

- The highest PE efficiency increase is reached in the “LCC optimal PE oriented” strategy followed by the “PE oriented” and “LCC optimal GHG and PE oriented” strategy. Additionally, “Image oriented” and “GHG oriented” strategy go under the guide value. The lowest PE efficiency increase results from the “Technology focus” strategy, such as in the case of the GHG emissions.

The both guide values (PE use and GHG emissions) are reached with the strategy combinations of life cycle costs, PE and GHG oriented, and with the “PE oriented” strategy. These strategies combined with life cycle costs are also relatively cost effective if the last two strategy steps are omitted (see Figure 1 and Figure 2).
In addition to the guide value of operation the guide value for a combination of operation and construction is presented in Figure 1 and Figure 2 (illustrated by the band between the guide values). This combination guide value is 11 $kgCO_{2eq}/m^2a$ for GHG emissions and 530 MJ/m^2a for total PE (primary energy) use.

	Description	Investment scrooge	Image oriented	GHG oriented	PE oriented	Technology focus	LCC optimal GHG oriented	LCC optimal PE oriented	LCC optimal GHG and PE oriented
M 1	Improvements of the thermal insulation of building envelope (building element and efficiency level)	Step 4 Roof insulation standard	Step 2 Windows Minergie Step 6 Façade Minergie	Step 3 Window , Minergie-P	Step 1 Façade Minergie			Step 1 Façade Minergie-P	Step 2 Façade Minergie-P
M 2	Choice of energy carrier/ Change of the heating system	Step 2 Gas	Step 5 Wood	Step 1 Wood	Step 3 DH	Step 3 HP geo	Step 2 HP geo	Step 2 DH	Step 3 HP geo
M 3	Implementation of ventilation system with heat recovery functions		Step 4		Step 2	Step 4		Step 7	Step 8
M 4	More efficient electricity services (such as lighting, cooling, appliances) from low efficiency level				Step 5 High efficiency level appliances and lighting	Step 2 Middle efficiency level appliances		Step 4 High efficiency level appliances and lighting	Step 6 High efficiency level appliances and lighting
M 5	Choice of energy supply mix (electricity)	Step 1	Step 3	Step 2			Step 1		Step 1
M 6	Control and regulation of the energy-related building systems and applications from the efficiency level C to B or A. (See explanation in section 2.4.4)	Step 3 C to B		Step 4 C to A, only thermal	Step 6 C to A	Step 1 C to B		Step 6 C to A	Step 7 C to A
M 7	On-site energy production: Implementation of solar thermal panels, PV or wind		Step 1	Step 5	Step 7	Step 5		Step 5	Step 4
M 8	Construction design and material choice with low embodied PE and GHG emissions				Step 4			Step 3	Step 5

Table 1: The summary of strategy steps of each main strategy applied to.the base case building from the construction period 1975-1990

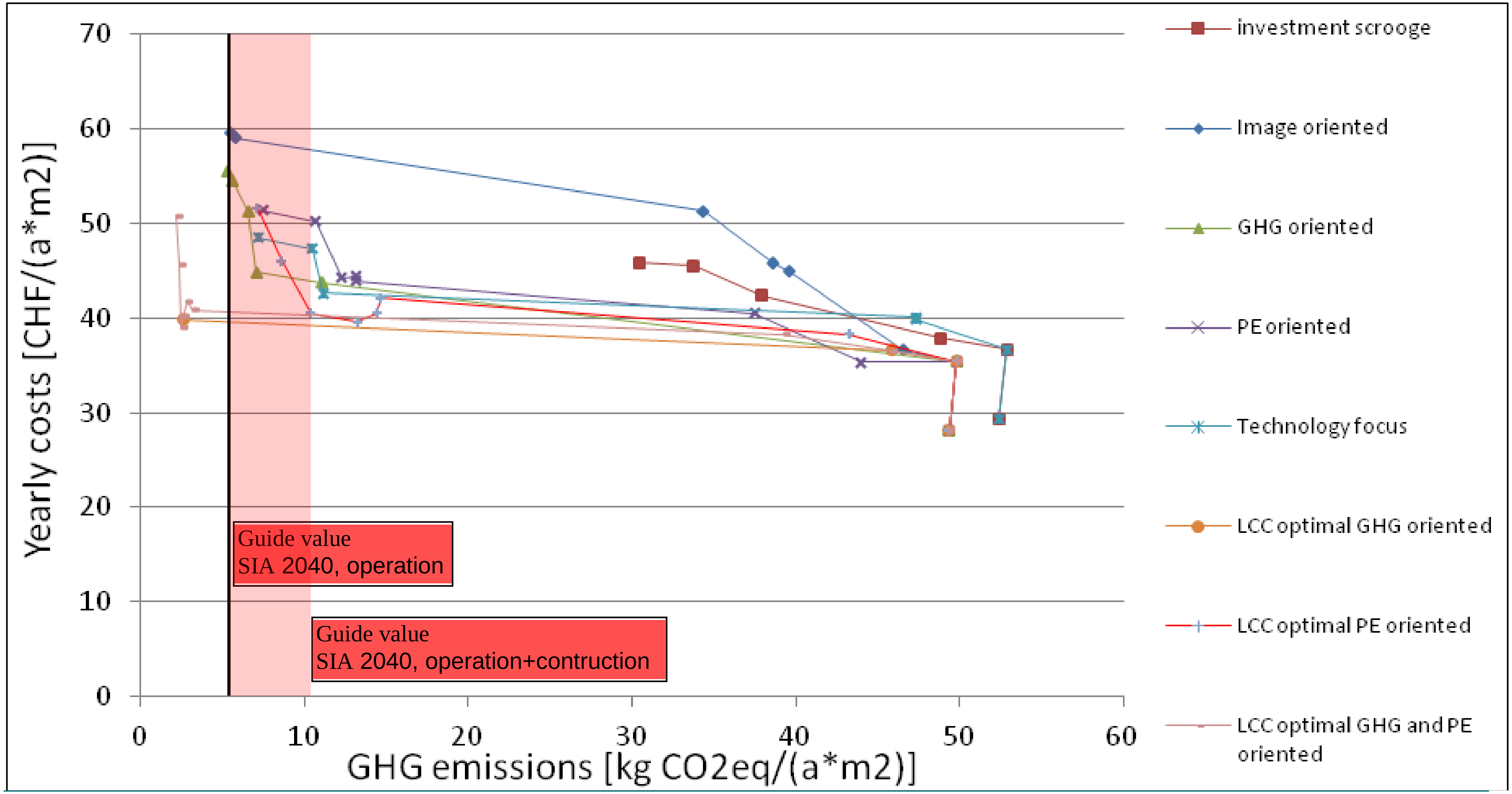

Figure 1: Yearly costs as a function of **GHG emissions** due to the strategy steps of the each main strategy (applied to the base case building from the construction period 1975-1990). The guide value of SIA 2040 is set for operation and the band is until the guide value which includes operation and construction.

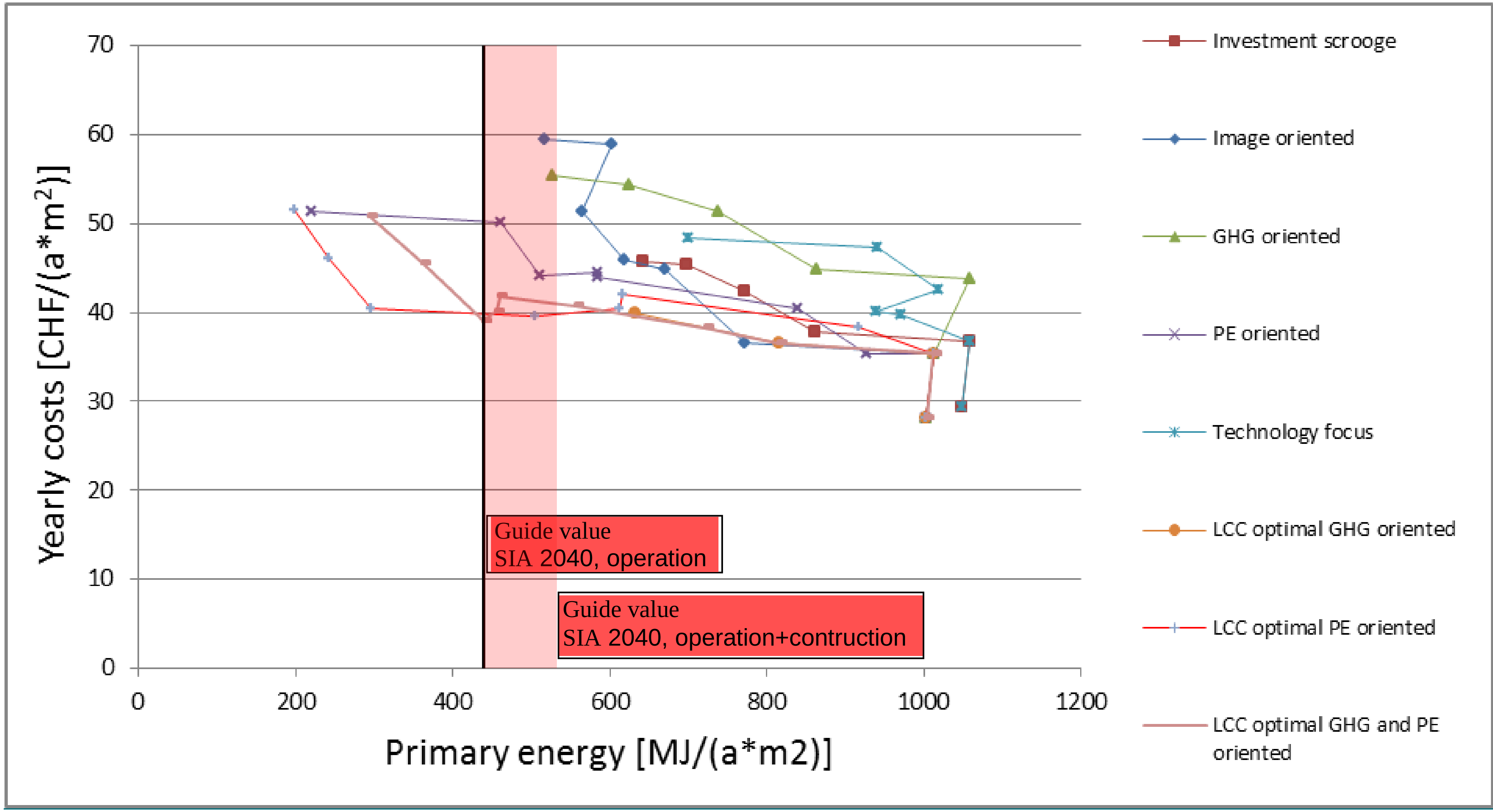

Figure 2: Yearly costs as a function of **primary energy use** due to the strategy steps of the each main strategy (applied to the base case building from the construction period 1975-1990). The guide value is set for operation and the band is until the guide value which includes operation and construction.

In addition to the strategy calculations sensitivity analysis are conducted in the Annex. First the sensitivity with respect to the building period is investigated. Instead of the building period 1975-1990 the period 1947-1975 is used with higher U-values of the elements of the building envelope and thus, increased heating demand before renovation. This sensitivity analysis reveals that the impacts of the measures that influence the heating demand are sensitive with respect to the construction period of the building due to the changing envelope insulation level and heating demand. These measures have a stronger (physical) effect and are more cost-effective for earlier building periods, for example 1947-1975, because then U-values are relatively high before renovation. However, the measures, that influence electricity use, are not sensitive for the construction period.

Additionally, the strategies, that meet the SIA 2040 guide values of 6 $kgCO_{2eq}/m^2a$ for GHG emissions and 450 MJ/m^2a for PE use, are not sensitive for the building period. They mainly meet the guide values with buildings from the building period of 1947-1975 as well as from 1975-1990 but the strategy “GHG oriented” does not reach the GHG emissions guide value and “Technology focus”, does not reach the PE guide value. This is caused mainly because the starting point in the earlier building period has higher PE use and GHG emissions.

The results are presented in the Annex.

The sensitivity of the yearly costs with respect to the combination of an installation of a heat pump and the insulation of the building envelope is investigated. Thereby, two heat pump cases are investigated:

- Heat pump power and efficiency are fixed after the heat pump investment. The power of the heat pump is determined for the energy need of the building before renovation, without increasing energy performance of the building envelope.
- Heat pump power is fixed after the investment. The power of the heat pump depends on the increase of the energy performance of the building envelope, which is carried out at the same time within the building retrofit. Therefore, the power of the heat pump is lower and its efficiency is higher than in the case of replacing first the heating system by a heat pump.

The results demonstrate the fact that the investment in the heat pump and building envelope efficiency should be conducted at the same time or in the order of insulation first and then heat pump installation. This order results to appropriate heat pump power selection which reduces the costs for the heat pump system remarkably.

The results are presented in the Annex.

Recommendations

The conclusion and recommendations for building owners and investors in existing residential multi-family houses are derived from the calculation results of the various generic strategies of this report but also from calculations performed within the context of the international part of the INSPIRE project. The following main recommendations can be applied for existing residential multi-family house owners and investors (see Chapter 4):

- To achieve more or less ambitious GHG mitigation and/or PE efficiency goals different strategies may be adopted. Mostly some few measures yield in a considerable effect with quite reasonable cost-effectiveness. The "last" steps in most of the strategies are much less cost-effective and rather not recommended from a private cost perspective.
- In terms of individual measures the following recommendations can be stated:
  - High efficient electricity services (such as lighting and appliances) are recommended with almost no reservation as they are cost effective or even economically viable.
  - Thermal improvements on the building envelope (insulation and more efficient windows) are cost effective if the energy carrier employed is primary energy and GHG intensive and especially in the case of low efficiency of existing building envelope before renovation. However, it is recommended to select carefully the building envelope parts to be insulated (mainly those that are not insulated at all) and efficiency level. The Minergie-P efficiency level leads to the relatively low additional benefit and high marginal costs if compared to Minergie. Thus, it is recommended to invest into renewable energy use or a green electricity mix, etc. that have constant or at least less increasing marginal costs than insulation.
  - Implementation of a ventilation system with a heat recovery function is not recommended from the cost-effectiveness point of view, but, from a normative point of view, if far reaching goals should be achieved, such systems are recommended notably in cases where the energy carrier is PE and GHG intensive. Furthermore, the consideration of the benefits from air ventilation regarding thermal and living comfort (air quality, noise prevention) as well as moisture and mold prevention may lead to a positive evaluation.
  - A heating system with a heat pump is an appropriate and interesting option to substantially reduce GHG emissions and non-renewable PE use, especially if low carbon electricity is used (certified or renewably produced on-site). From a long term cost perspective a reduction of the energy needs of the building by improving the energy performance of the building envelope prior to the installation of the heat pump is recommended, especially for ground source heat pumps. Thereby heat load and load dependent system costs (length of the borehole and size of the heat pump) can be reduced and the efficiency of the heat pump increased.
    However, the combination of the lower insulation level and larger size of the heat pump heating system may lead to lower yearly costs than the combination of the higher insulation level and smaller size of the heat pump heating system. See the "LCC optimal, GHG and PE oriented" strategy variants on the pages 110 – 112.

Thus, the heat pump heating system is recommended with the carefully selected insulation level (efficiency and the number of the building elements should not increase too much).

Additionally, a district heating system reduces GHG emissions and PE use significantly and is recommended if the energy carrier generating the heat is renewable or waste.

Wood heating systems do substantially reduce carbon emissions. Regarding primary energy use, they do distinctly reduce non-renewable primary energy use but not total primary energy use, which might even increase compared to an efficient oil or gas heating system.

- The composition of the package of retrofit measures matters: An appropriate selection of retrofit measures can result in high GHG emissions mitigation and PE use reduction with comparable or even lower life cycle costs than a suboptimal selection of measures. (See "Investment scrooge" and "LCC optimal GHG and PE oriented" strategies in Figure 1 and Figure 2). Thus, it is recommended to carefully evaluate the strategies with the INSPIRE tool.
- Given the decreased prices of PV modules, which allows for a more or less competitive PV installation if assuming a net metering regime PV is recommended due to quite favorable cost effectiveness (as compared to other measures).
- Embodied energy use in the case of building retrofit usually doesn't play the same role as in the case of new building construction. The building already exists and the scope of action to reduce embodied energy use within building retrofit is limited, except in the case of building extensions. The selection of lower embodied energy content in the envelope insulation measures reduces only slightly GHG emissions and PE use, but might still be considered as an additional criterion.

Finally, it is recommended to ex-ante assess the effect of different combinations of measures (for instance using the INSPIRE tool).

Zusammenfassung

Dieser Bericht ist eines der Ergebnisse des internationalen Projekts INSPIRE das im Rahmen des Forschungsverbunds ERACOBUILD durchgeführt wurde. Der Bericht stellt einen der Beiträge des Schweizerischen Projektteils von INSPIRE[2] dar und thematisiert verschiedene Erneuerungsstrategien für Gebäude in der Schweiz. Ziel und Umfang dieses Projektteils, der von verschiedenen wichtigen Akteuren des nachhaltigen Bauens in der Schweiz unterstützt wurde (s. Impressum), beziehen sich auf die Schweiz (weitere Projektergebnisse sind in einem Bericht zum internationalen Projektteil zu finden).

Auf den Gebäudesektor entfällt ein grosser Anteil am gesamten Endenergieverbrauch der Schweiz. Während jedoch die Energieeffizienz von Neubauten aufgrund energetischer Anforderungen kontinuierlich steigen, stellt die energetische Verbesserung des Gebäudebestands nach wie vor eine bedeutende Herausforderung der Zukunft dar. Die Bewältigung dieser Herausforderung erfordert die Identifikation von kostenoptimalen Erneuerungsstrategien, um eine gezielte Reduktion von Energieverbrauch und CO_2-Emissionen im Bereich der Gebäuderenovation zu erreichen. In diesem Bericht werden solche generische Strategien für einen repräsentativen Mehrfamilienhaustyp der Schweiz identifiziert, beurteilt und verglichen.

Dazu wurde das INSPIRE[3] Tool eingesetzt, dessen Entwicklung ein weiterer wichtiger Beitrag des INSPIRE Projekts ist. Mit dem Tool können energetische, ökologische und ökonomische Indikatoren sowie Treibhausgasreduktions- und Primärenergiereduktionsstrategien von Gebäuden berechnet werden. Es können also Trade-offs und Synergien zwischen verschiedenen Massnahmentypen untersucht und Strategien, die auf die kosteneffiziente Reduktion des Primärenergieverbrauchs und der Treibhausgasemissionen zielen, beurteilt werden.

Das Tool beinhaltet eine Datenbank mit empirischen techno-ökonomischen Charakteristika verschiedener Massnahmen, welche in sieben strategische Ansatzpunkte eingeteilt werden können: (i) Wärmedämmung, (ii) Heizsysteme mit erneuerbaren Energien, (iii) Lüftungsanlage mit Wärmerückgewinnung, (iv) effiziente strombasierte Anwendungen (Beleuchtung, Kühlung und weitere Anwendungen), (v) primärenergieeffiziente und treibhausgasarme Energieträgermix, (vi) Steuerung und Regelung mittels Gebäudeautomation, (vii) Vor-Ort-Produktion von erneuerbaren Energien und (viii) Konstruktionsweise und Materialien mit geringer grauer Energie und Treibhausgasemissionen.

Für zwei Referenzfälle und bis zu acht Renovierungspakete von Massnahmen können ökonomische und ökologische Indikatoren abgebildet werden: Investitionen, jährliche Kosten, gesamter und nicht-erneuerbarer Primärenergieverbrauch sowie Treibhausgasemissionen. Durch die Nutzung aktueller empirischer Kosten- und Preisdaten werden die

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[2] INSPIRE: Integrated strategies and policy instruments for retrofitting buildings to reduce primary energy use and GHG emissions

[3] **I**nstrument für **S**trategie- und **P**rojektentwicklung - **I**ntegration von **R**essourcen und **E**missionen

Kosteneffizienz und die Wirtschaftlichkeit der Massnahmen von einem Jahreskosten-Standpunkt aus untersucht. Anhand des Tools kann darüber hinaus der Einfluss von Faktoren wie die Ausgangssituation, Umfang und Kosten von Massnahmen, Verzinsung und Energiepreiserwartungen aufgezeigt werden.

Untersuchungsgegenstand

Das Ziel der techno-ökonomischen Beurteilung von energetischen Gebäudeerneuerungsstrategien dieser Studie ist es, die folgenden Forschungsfragen systematisch zu betrachten:

- Wie hoch ist der Beitrag von Erneuerungsmassnahmen, welche die Energieeffizienz der Gebäudehülle steigern, dies im Vergleich zur Nutzung erneuerbarer Energien und zwar in Bezug auf resultierende Kosten, Treibhausgasemissionen und gesamten Primärenergieverbrauch?
- Wie ist die Relation zwischen den oben genannten Gebäudesanierungsmassnahmen im Vergleich zu Optionen in den Bereichen Gebäudetechnologie, Beleuchtung und Haushaltsgeräte?
- Wie gross ist der Einfluss auf die Ergebnisse, wenn die graue Energie („Erstellung“ gemäss SIA Effizienzpfad Gebäude, MB 2040) und die damit verbundenen Emissionen in die Betrachtung einbezogen werden?
- Wie stark werden die Ergebnisse beeinflusst, wenn weitere Optionen wie Vor-Ort-Energieproduktion oder der Bezug von Energie mit geringem CO_2- und Primärenergiegehalt einbezogen werden?
- Welche Schlüsse können aus den Ergebnissen als Empfehlungen für Gebäudeeigentümer und Investoren gezogen werden?

Methodik

Die diesem Bericht zu Grunde liegenden Berechnungen konzentrieren sich auf Wohngebäude ohne Kühlbedarf. Die eingesetzte Methodik betrachtet weder gebäudebezogene Mobilität noch Zusatznutzen von Erneuerungsmassnahmen. In die Betrachtung einbezogen werden jedoch die „graue Energie“ und die „grauen“ Treibhausgasemissionen (gesamte Primärenergie inkl. Umweltwärme und THG „Erstellung)“ sowie vorgelagerte Lebenszyklusprimärenergieverbräuche der Energieträger und damit verbundene Treibhausgasemissionen.

Das methodische Vorgehen beinhaltet folgende Schritte:

Schritt 1: Definition von Basisparametern: Zinsentwicklung und Energiepreise; Zeitspanne der Auswertung; Strommix (Abschnitt 2.2)

Schritt 2: Charakterisierung des Gebäudebestands und Auswahl von Gebäuden für die Fallstudien (Abschnitt 2.2)

Schritt 3: Erhebung von techno-ökonomischen Daten zu Massnahmen zur Reduktion von Primärenergie und Treibhausgasemissionen.

Schritt 4: Definition einer Referenzsituation und verschiedenen Strategien und ihren Massnahmen zur Reduktion des Primärenergieverbrauchs oder der Treibhausgasemissionen, dies für verschiedene Typen von Eigentümern (Kapitel 3)

Schritt 5: Berechnung der energetischen Wirkung der Massnahmen (Methodik, s. Kapitel 2.1 und 2.4)

Schritt 6: Berechnung der Kosteneffizienz, d.h. des Einflusses auf Treibhausgasemissionen, Primärenergieverbrauch und Lebenszykluskosten diverser Massnahmen im Kontext verschiedener Strategien (Kapitel 3)

Schritt 7: Vergleich verschiedener Massnahmen und Strategien (Massnahmenpakete) und Schlussfolgerungen bezüglich kosteneffizienten und nachhaltigen Massnahmenpaketen an der Gebäudehülle, dem Heizsystem und der energiebezogenen Gebäudeausstattung (Kapitel 3.7)

Schritt 8: Empfehlungen für Gebäudeeigentümer und Investoren (Kapitel 4)

Die Schritte 1, 2 und 3 werden detailliert in Kapitel 2 beschrieben. Die Basisparameter der Berechnungen wie Energiepreise, Zins- und Diskontsätze, Emissions- und Primärenergiefaktoren sowie Klimadaten werden in Abschnitt 2.2 definiert und dargestellt.

Ein Referenzgebäude für die Berechnungen wird auf Basis der Schweizer Bautypologie ausgewählt. Das Hauptaugenmerk des Berichts liegt dabei auf Mehrfamilienhäusern verschiedener Bauperioden. Gemäss der Gebäudestatistik des Bundesamts für Statistik bzgl. des Jahres 2000 sind Heizsysteme mit fossilen Energieträgern von besonderer Relevanz. Andere Heizsysteme werden im Rahmen der Erneuerungsstrategien berücksichtigt.

Die techno-ökonomischen Daten von Bau-, Umbau und Gebäudetechnologiemassnahmen zur Senkung von Treibhausgasemissionen und Primärenergieverbrauch stammen aus verschiedenen Quellen wie CRB (Gebäudekonstruktion), Fernwärme Zürich und Amstein+Waltert (Heizsysteme) und Siemens (Gebäudeautomation). Die verwendeten techno-ökonomischen Daten werden in Kapitel 2.4 dargestellt.

Um die Vielfalt verschiedener Eigentümertypen und ihre individuellen Präferenzen abzubilden, wurden vier verschiedene Typen von Strategien definiert:

I. Investitionsavers

II. Umweltfokussiert

III. Technologiefokussiert

IV. Lebenszykluskostenoptimiert

Jeder Strategietyp beinhaltet zusätzliche Varianten, um eine Sensitivität für verschiedene Massnahmen zu berücksichtigen. Die detaillierten Strategieberechnungen und –ergebnisse werden in Kapitel 3 dargestellt. Die detaillierten Ergebnisse der Anwendung jeder Hauptstrategie auf die Referenzsituation werden in Kapitel 3.7 zusammengefasst und verglichen. Zusätzlich werden die Grenzkosten und -nutzen jeder Massnahme als Funktion der Reduktion der Treibhausgasemissionen und der Steigerung der Primärenergieeffizienz für die verschiedenen Strategien dargestellt.

Ergebnisse

Im Vergleich zum Referenzfall 2 zeigen die meisten Strategien eine leicht steigende Tendenz der Kosten-Treibhausgas- und Kosten-Primärenergiebeziehungen durch die ersten Schritte der Strategie (Figur 3 und Figur 4). Eine leicht steigende Kurve als Funktion **niedrigerer** Treibhausgasemissionen und Primärenergieverbräuche (d.h. von rechts nach links in der jeweiligen Figur) bedeutet, dass die Massnahmen nicht wirtschaftlich sind, aber beinahe; sie können als kosteneffizient bezeichnet werden. Bei einigen wirtschaftlichen Massnahmen ergeben sich fallende Kurven. Die letzten Massnahmenschritte der betrachteten Strategien bewirken in der Regel einen steilen Anstieg am Ende der Kurve.

Die verschiedenen Strategien sind in Table 2 in der Übersicht aufgeführt. Die Ergebnisse der Jahreskosten als Funktion der Reduktion der Treibhausgasemissionen und des gesamten Primärenergieverbrauchs sind für jede Strategie in Figur 3 und Figur 4 dargestellt. Zwei der Strategien erreichen die SIA 2040 Richtwerte „Betrieb“ für Treibhausgasemissionen für Wohngebäude (6 kg CO_{2eq}/m^2a) vollständig, zwei sehr knapp und weitere drei näherungsweise. Drei Strategien erreichen die SIA 2040 Richtwerte für den gesamten Primärenergieverbrauch „Betrieb“ (450 MJ/m^2a):

- Alle Strategien vermögen die Treibhausgasemissionen deutlich zu reduzieren, in der Regel um mehr als 70 %. Der Richtwert „Betrieb“ des Merkblatts (MB) SIA 2040 wird bei vier Strategien erreicht (Umweltimage- und Umweltklimawandelorientiert) oder unterschritten (Lebenszykluskosten- mit Klimawandel- bzw. mit Klimawandel- und Primärenergie-orientiert). Bei weiteren drei Strategien gelingt im Vergleich zur Ausgangslage eine starke Annäherung an den Richtwert. Am geringsten ist die Reduktion bei der investitionsaversen Strategie, in welcher nur rund 50% der maximalen Reduktion erreicht wird.

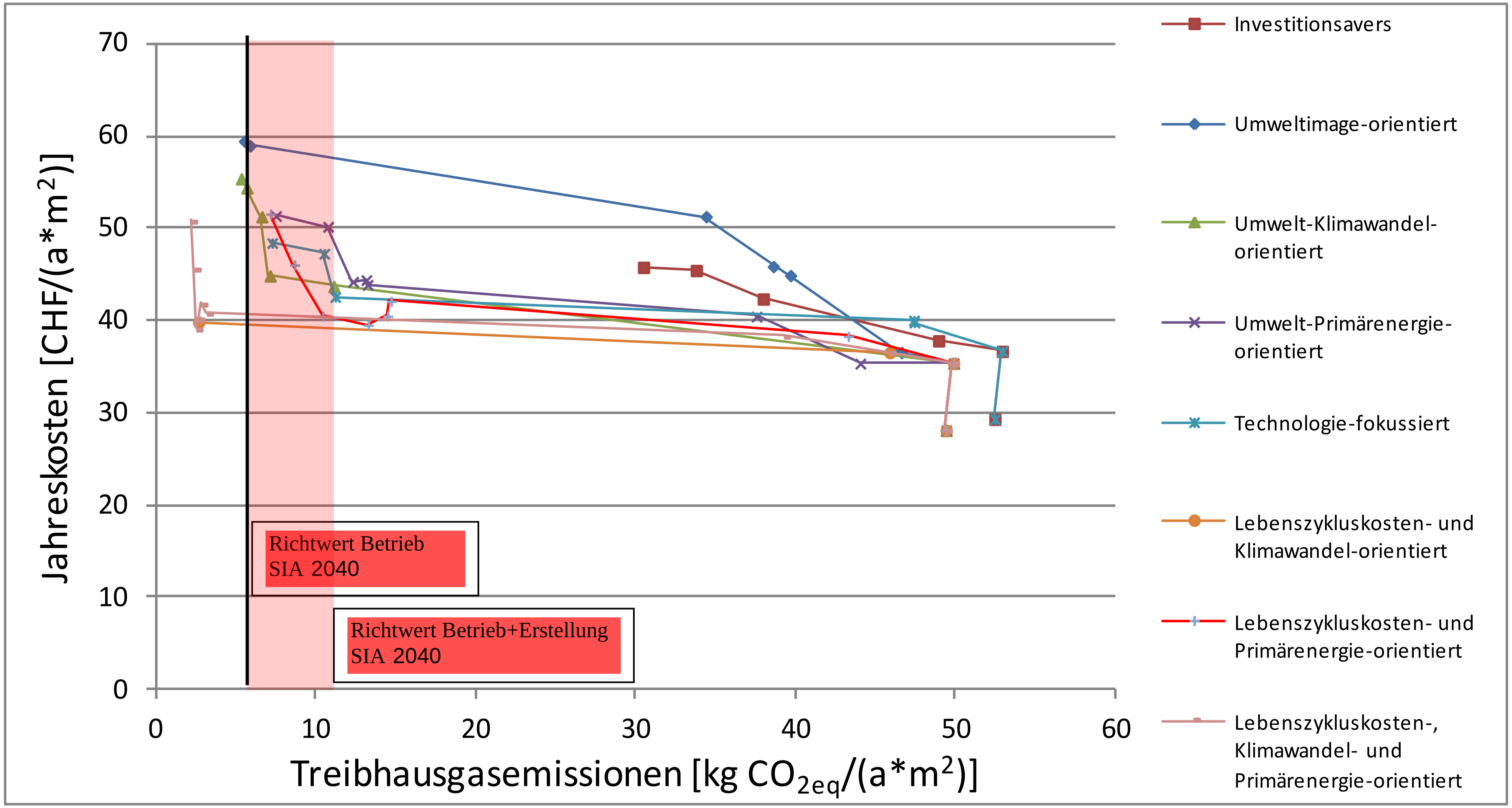
- Bei der gesamten Primärenergie wird die höchste Steigerung durch die Strategien „Lebenszykluskosten- und Primärenergie-orientiert“, „Lebenszykluskosten-, Klimawandel- und Primärenergieorientiert“ und „Umwelt-Primärenergie-orientiert“ erzielt. Zudem unterschreiten die Strategien „Umweltimage-orientiert“ und „Umwelt-Klimawandel-orientiert“ den Richtwert des Vernehmlassungsentwurfs der SIA 2040. Die geringste Steigerung der Primärenergieeffizienz resultiert, ähnlich wie bei den THG-Emissionen, in der „Technologie-fokussiert“ und „Investitionsavers“ Strategie.

Beide Richtwerte (THG und gesamte PE) werden einzig durch die kombinierte Strategie „Lebenszykluskosten-, Klimawandel- und Primärenergieorientiert“ erreicht und zwar relativ kosteneffizient, wenn die beiden letzten Massnahmenschritte weggelassen.

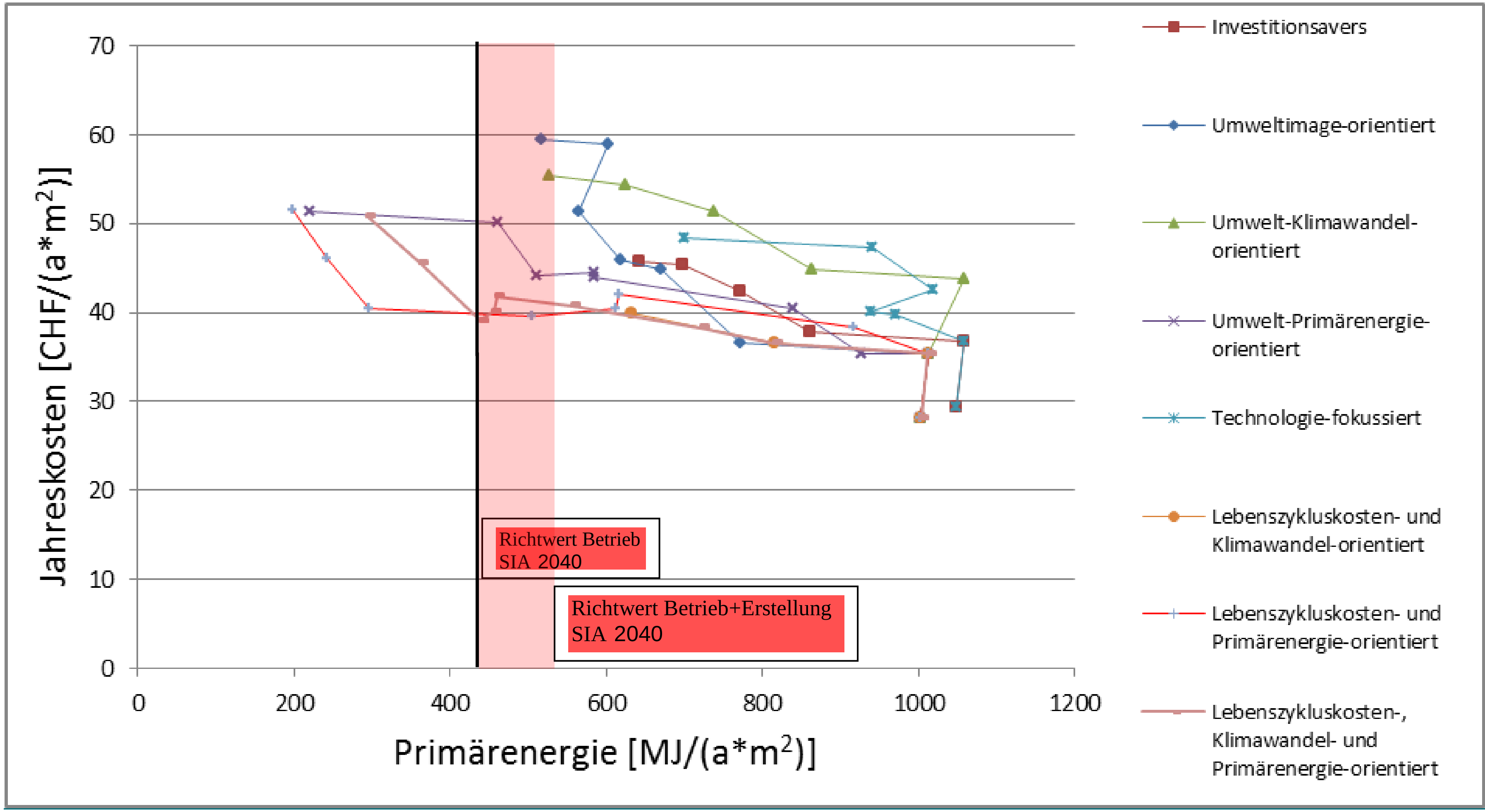
In Ergänzung zum Richtwert „Betrieb“ wird in Figur 3 und Figur 4 die Summe der Richtwerte „Betrieb“ und „Erstellung“ dargestellt (11 $kgCO_{2eq}/m^2a$ bei den Treibhausgasemissionen und 530 MJ/m^2a bei der gesamten PE). Bzgl. der gesamten Primärenergie wird hierbei auf den Vernehmlassungsentwurf der SIA 2040 Bezug aus dem Jahr 2010 genommen.

	Beschreibung	Investitionssavers	Umwelt-image-orientiert	Umwelt-klimwandel-orientiert	Umwelt-primärenergieorientiert	Technologie-fokussiert	Lebenszyklus-benszyklus-kosten- und klimawandel-orientiert	Lebenszyklus-kosten- und primärenergie -orientiert	Lebenszyklus-kosten-, klima-wandel- und primärenergie-orientiert
M 1	Verbesserungen des Wärmeschutzes durch Wärmedämmung und Fensterersatz der Gebäudehülle	Schritt 4 Dachwärmedämmung Standard	Schritt 2 Fenster Minergie Step 6 Fassade, Minergie	Schritt 3 Fenster Minergie-P	Schritt 1 Fassade Minergie			Schritt 1 Fassade Minergie-P	Schritt 2 Fassade Minergie-P
M 2	Wahl des Energieträgers / Wechsel der Heizungsanlage	Schritt 2 Gas statt Öl	Schritt 5 Holz statt Ol	Schritt 1 Holz statt Ol	Schritt 3 Fernwärme statt Ol	Schritt 3 WP geo statt Ol	Schritt 2 WP geo statt Ol	Schritt 2 Fernwärme statt Ol	Schritt 3 WP geo statt Ol
M 3	Einbau einer Lüftungsanlage mit Wärmerückgewinnung		Schritt 4		Schritt 2	Schritt 4		Schritt 7	Schritt 8
M 4	Effizientere Stromanwendungen (wie z.B. Beleuchtung, Kühlung, Haushaltsgeräte)				Schritt 5 Hocheffiziente Haushaltgeräte und Beleuchtung	Schritt 2 Mitteleffeziente Haushaltgeräte		Schritt 4 Hocheffiziente Haushaltgeräte und Beleuchtung	Schritt 6 Hocheffiziente Haushaltgeräte und Beleuchtung
M 5	Wahl des Strommixes (weniger primärenergie- und treibhausgasintensiv)	Schritt 1	Schritt 3	Schritt 2			Schritt 1		Schritt 1
M 6	Steuerung und Regelung der energetischen Gebäudesysteme und Anwendungen von Effizienzlevel C bis B oder A. (gemäss SIA 386.110)	Schritt 3 C zu B		Schritt 4 C zu A, nur thermisch	Schritt 6 C zu A	Schritt 1 C zu B		Schritt 6 C zu A	Schritt 7 C zu A
M 7	Vor-Ort-Produktion von erneuerbaren Energien: thermische Solar-, PV- oder Windanlage		Schritt 1	Schritt 5	Schritt 7	Schritt 5		Schritt 5	Schritt 4
M 8	Konstruktiver Aufbau und Materialwahl mit geringer grauer Energie und Treibhausgasemissionen				Schritt 4			Schritt 3	Schritt 5

Table 2: Darstellung der Strategieschritte M1 bis M8 für die verschiedenen Hauptstrategien, angewandt auf das Referenzgebäude der Bauperiode 1975 – 1990



Figur 3: Jahreskosten als Funktion von Treibhausgasemissionen für die Strategieschritte jeder Hauptstrategie (angewandt auf das Referenzgebäude der Bauperiode 1975 – 1990) und Richtwerte SIA 2040 Betrieb und Betrieb+Erstellung von SIA 2040 (Entwurf). .



Figur 4: Jahreskosten als Funktion des gesamten Primärenergieverbrauchs für die Strategieschritte jeder Hauptstrategie (angewandt auf das Referenzgebäude der Bauperiode 1975 – 1990) und Richtwerte SIA 2040 Betrieb und Betrieb+Erstellung von SIA 2040 (Entwurf).

Als Ergänzung der Berechnungen verschiedener Strategien wurden zwei Sensitivitätsanalysen durchgeführt (s. Anhang). Zunächst wurde dabei die Sensitivität bezüglich der Bauperiode untersucht. Anstelle der Bauperiode 1975-1990 wurde die Bauperiode 1947-1975 mit höheren U-Werten der Gebäudehülle und somit mit einem erhöhten Wärmebedarf zu Grunde gelegt.

Die Sensitivitätsanalyse bezüglich der Bauperiode ergibt, dass Wärmedämmungsmassnahmen aufgrund des geänderten Wärmedämmungsgrads der Gebäudehülle und dem daraus resultierenden Wärmebedarf, sensitiv bezüglich der Bauperiode sind. Diese Massnahmen haben eine grössere Wirkung und tiefere Grenzkosten, wenn sie auf Gebäude angewendet werden, welche aus frühen Bauperioden stammen, wie z.B. 1947-1975. Grund hierfür sind die relativ hohen Ausgangs-U-Werte, welche in Folge von Massnahmen zur Gebäudedämmung verbessert werden können. Im Gegensatz dazu sind Massnahmen, welche den Strombedarf beeinflussen, nicht sensitiv bezüglich der Bauperiode.

Die Gesamtergebnisse der verschiedenen Strategievarianten weisen keine Sensitivität bezüglich der Bauperiode auf. Beispielsweise erreichen zwar die meisten Strategien, welche die SIA 2040 Zielsetzungen von 6 kg CO_{2eq}/m^2a für Treibhausgasemissionen und 450 MJ/m^2a für Primärenergieverbrauch für Gebäude der Bauperiode 1975-1990 erfüllen, diese Zielsetzungen auch bei der Bauperiode 1947-1975. Es sind jedoch folgende Ausnahmen festzuhalten: Mit der Strategie „Treibhausgas orientiert“ wird der Richtwert bzgl. Treibhausgasen nicht erreicht und mit den Strategien „Technologie-fokussiert“ wird die PE-Richtwerte nicht erreicht. Dies ist hauptsächlich auf den höheren Wert im IST-Zustand zurück zu führen.

Die Detailergebnisse der Sensitivitätsanalysen sind im Anhang dargestellt.

In einer weiteren im Anhang dargestellten Sensitivitätsanalyse wird die Sensitivität der Jahreskosten bezüglich der Massnahmenkombination einer Wärmepumpe mit und ohne Wärmedämmung der Gebäudehülle untersucht. Dazu werden zwei Fälle betrachtet:

- Leistung und Effizienz der Wärmepumpe werden nach dem Einbau der Wärmepumpe fixiert. Die beiden Parameter bleiben selbst unter erhöhter Effizienz der Gebäudehülle unverändert.
- Die Leistung der Wärmepumpe wird nach ihrem Einbau fixiert, jedoch wird die Effizienz der Wärmepumpe in Abhängigkeit der Effizienz der Gebäudehülle verändert.

Die beschriebene Sensitivitätsanalyse ergibt, dass die Investitionen in eine Wärmepumpe und in die Effizienz der Gebäudehülle entweder gleichzeitig erfolgen oder zunächst die Investition in die Gebäudehülle und im Anschluss in die Installation der Wärmepumpe getätigt werden sollte. Dies führt zu einer richtig dimensionierten Wahl der Wärmepumpenleistung und somit zu einer Kostenreduktion.

Die Detailergebnisse der Sensitivitätsanalysen sind im Anhang dargestellt.

Empfehlungen

Sowohl das Fazit als auch die Empfehlungen für Gebäudeeigentümer und Investoren bestehender Wohngebäude-Mehrfamilienhäusern werden von den Ergebnissen der Berechnungen der verschiedenen generischen Strategien dieses Berichts, aber auch von den Berechnungen im Kontext des internationalen Teils des INSPIRE Projekts abgeleitet. Die folgenden wichtigsten Empfehlungen können für die Eigentümer oder Investoren eines bestehenden Mehrfamilienhauses formuliert werden (s. auch Kapitel 4):

- Um mehr oder weniger ehrgeizige Treibhausgasreduktionen und / oder Primärenergieeffizienzziele zu erreichen, können verschiedene Strategien verfolgt werden. In der Regel führen einige wenige Massnahmen zu einem beachtlichen Effekt mit vertretbarer Kosteneffizienz. In den meisten Strategien sind die „letzten“ Schritte deutlich weniger kosteneffizient und daher eher nicht zu empfehlen.
- In Bezug auf individuelle Massnahmen können die folgenden Empfehlungen festgehalten werden:
    - Hocheffiziente Stromanwendungen (wie Beleuchtung, Geräte und weitere Anwendungen) werden fast ohne Einschränkung empfohlen, da sie in der Regel kosteneffizient oder sogar wirtschaftlich sind.
    - Thermische Verbesserungen der Gebäudehülle (Wärmedämmung und Ersatz von Fenstern) sind kosteneffizient, falls es sich um einen primärenergie- und treibhausgasintensiven Energieträger handelt sowie insbesondere im Fall von noch geringer Effizienz der bestehenden Gebäudehülle. Es ist entsprechend zu empfehlen, die zu dämmenden Gebäudeteile mit Bedacht auszuwählen und vor allem auf die noch ungedämmten Bauteile zu fokussieren. Der Schritt von Minergie zu Minergie-P bewirkt eine relative geringe Steigerung der Energieeffizienz und führt entsprechend zu relativ hohen Grenzkosten. Deshalb wird empfohlen, eher in andere Massnahmen wie erneuerbare Energien, grünen Strom etc. zu investieren, weil dies konstante oder weniger stark ansteigende Grenzkosten haben.
    - Die Installation einer Lüftungsanlage mit Wärmerückgewinnung wird rein aus Sicht der Kosteneffizienz nicht empfohlen, jedoch aus normativer Sicht: Sollen weitreichende Ziele realisiert werden, so sind solche Systeme zu empfehlen, vor allem wenn ein primärenergie- und treibhausgasintensiver Energieträger vorliegt. Auch der Einbezug weitergehender Nutzen im Bereich Wohnkomfort (Luftqualität, Lärmschutz) und Feuchtigkeitsschutz kann zu einer positiven Bewertung führen.
    - Ein Heizsystem mit Wärmepumpe ist eine geeignete Wahl, um Treibhausgasemissionen und den nicht-erneuerbaren Primärenergieverbrauch zu senken, insbesondere falls CO_2-armer Strom (zertifiziert oder vor-Ort produziert) verwendet wird. Grundsätzlich ist es aus der Langfristperspektive auch zu empfehlen, die Gebäudehülle vor dem Installieren einer Wärmepumpe energetisch zu erneuern, v.a. im Fall von Erdsonden-WP. Damit können leistungsabhängige Kosten (Sondenlänge und Anlagengrösse) reduziert werden. Es ist jedoch zu betonen, dass

diese Kosteneinsparungen bei der Wärmepumpe allein eine umfassende Wärmedämmung der Gebäudehülle nicht rechtfertigen; eine moderate Erneuerung der Gebäudehülle ist hierfür ausreichend.
Darüber hinaus führt ein Heizsystem auf Basis von Fernwärme sowohl zu einer deutlichen Senkung der Treibhausgasemissionen als auch des Primärenergieverbrauchs, falls die Fernwärme vorwiegend mit Abfall und/oder erneuerbaren Energien erzeugt wird. Ein Holzheizsystem ist zwar keine geeignete Wahl zur Senkung des gesamten, wohl aber des nicht-erneuerbaren Primärenergieverbrauchs sowie der Treibhausgasemissionen.

- Eine geeignete Wahl von Erneuerungssmassnahmen kann im Vergleich zu einer sub-optimalen Massnahmenwahl zu einer starken Reduktion der Treibhausgasemissionen und des Primärenergieverbrauchs führen, dies bei vergleichbaren Lebenszykluskosten (s. Investitionsaverse und „Lebenszykluskosten-, Klimawandel- und Primärenergieorientierte“ Strategien in Figur 3 und Figur 4). Es wird also empfohlen, die in Betracht gezogene Strategie jeweils mit dem INSPIRE Tool zu evaluieren.

- In Anbetracht der gesunkenen Preise der PV-Module, welche die Gesamtkosten einer PV-Anlage senken und unter der Voraussetzung von Net-metering, wird PV wegen recht vorteilhafter Kosteneffizienz ebenfalls empfohlen.

- Die Wahl von Wärmedämmungsmassnahmen an der Gebäudehülle mit geringem grauem Energiegehalt reduziert die Treibhausgasemissionen und den Primärenergieverbrauch nur geringfügig. Vor allem im Fall von Neubauten sollte sie jedoch als zusätzliches Kriterium in Betracht gezogen werden.

Abschliessend wird empfohlen, die Effekte verschiedener Massnahmenkombinationen ex-ante zu vergleichen. Hierzu eignet sich z.B. das INSPIRE Tool.

Résumé

Ce rapport est l'un des résultats du projet international INSPIRE, réalisé dans le cadre du réseau de recherche ERACOBUILD. Le rapport présente l'une des contributions du sous-projet suisse de INSPIRE[4] et thématise diverses stratégies de rénovation pour les bâtiments en Suisse. L'objectif et le volume de ce sous-projet, soutenu par différents importants acteurs de la construction durable en Suisse (v. Impressum), se rapportent à la Suisse (d'autres résultats de projet sont présentés dans un rapport sur le sous-projet international).

Le secteur du bâtiment absorbe une grande partie de la consommation totale d'énergie finale en Suisse. Alors que l'efficience énergétique des nouvelles constructions augmente continuellement en raison des exigences énergétiques, l'amélioration énergétique des bâtiments existants demeure encore et toujours un défi significatif pour l'avenir. La maîtrise de ces défis nécessite l'identification de stratégies de rénovation à coûts optimums, afin d'attendre une réduction ciblée de la consommation d'énergie et des émissions de CO_2 dans le secteur de la rénovation de bâtiments. Ce rapport identifie, évalue et compare de telles stratégies génériques pour un type d'immeuble collectif représentatif en Suisse.

L'outil INSPIRE[5] est utilisé à cet effet, dont le développement constitue une autre contribution majeure du projet INSPIRE. Cet outil permet de déterminer les indicateurs énergétiques, écologiques et économiques ainsi que les stratégies de réduction des gaz à effet de serre et les stratégies d'efficacité énergétique primaire des bâtiments. Il est donc possible d'examiner des Trade-offs et des synergies entre différents types de mesures et d'évaluer des stratégies qui visent la réduction rentable de la consommation d'énergie primaire et des émissions de gaz à effet de serre.

L’outil renferme une base de données avec les caractéristiques techno-économiques empiriques de différents types de mesures pouvant être répartis en sept points de départ stratégiques: (i) isolation thermique, (ii) systèmes de chauffage avec énergies renouvelables, (iii) système d’aération à récupération de chaleur, (iv) applications de l’électricité (éclairage, réfrigération et autres applications), (v) bouquet énergétique à haute efficience énergétique primaire et pauvre en gaz à effet de serre, (vi) commande et réglage de l’immotique et (vii) production d’énergie sur place (viii) type de construction et matériaux à faible énergie grise et émissions de gaz à effet de serre. Des indicateurs économiques et écologiques peuvent être reproduits pour deux cas de référence et jusqu’à huit paquets de mesures de rénovation: investissements, coûts annuels, consommation d’énergie primaire totale et non renouvelable ainsi qu’émission de gaz à effet de serre. La rentabilité et l’efficacité économique des mesures sont examinées du point de vue des coûts annuels en utilisant des données de coûts et de prix empiriques actuelles. L’outil permet en outre de montrer l’influence de facteurs tels

[4] INSPIRE: Integrated strategies and policy instruments for retrofitting buildings to reduce primary energy use and GHG emissions

[5] Instrument pour le développement de stratégies et projets – intégration de ressources et émissions

que la situation de départ, l'étendue et les coûts des mesures, le taux d'intérêt et les prix de l'énergie attendus.

Objet de l'étude

L'évaluation techno-économique de stratégies d'assainissement de bâtiments basse consommation de cette étude a pour but de considérer systématiquement les questions de recherche suivantes:

- Quelle est la contribution des mesures d'assainissement augmentant l'efficience énergétique de l'enveloppe du bâtiment par rapport à l'utilisation d'énergies renouvelables, en ce qui concerne les coûts en résultant, les émissions de gaz à effet de serre et la consommation d'énergie primaire?
- Quelle est la relation entre les mesures d'assainissement susmentionnées et les options dans les domaines de la technologie du bâtiment, de l'éclairage et des appareils ménagers?
- Quelle est l'influence sur les résultats si l'on tient compte de l'énergie grise («construction» selon SIA2040) et des émissions apparentées?
- Dans quelle mesure les résultats sont-ils influencés si on inclut d'autres options comme la production d'énergie sur place ou l'achat d'énergie à teneur moindre en CO_2 et en énergie primaire?
- Quelles conclusions peut-on tirer des résultats en guise de recommandations pour les propriétaires d'immeubles et les investisseurs?

Méthode

Les calculs sous-jacents à ce rapport se concentrent sur les immeubles d'habitation sans besoin de refroidissement. La méthode utilisée ne considère ni la mobilité dans le domaine du bâtiment ni des avantages supplémentaires de mesures d'assainissement. L'observation intègre toutefois «l'énergie grise» et les émissions de gaz à effet de serre «grises» (énergie primaire et production de gaz à effet de serre) ainsi que les consommations d'énergie primaire en amont des cycles de vie des sources d'énergie et des émissions de gaz à effet de serre qui y sont liées.

La méthodologie en étapes:

Etape 1: Définition de paramètres de base: évolution des taux d'intérêt et prix de l'énergie; période de l'évaluation; mix d'électricité (chapitre 2.2)

Etape 2: Caractérisation des bâtiments existants et sélection de bâtiments pour les études de cas (chapitre 2.2)

Etape 3: Saisie de données techno-économiques sur les mesures de réduction de l'énergie primaire et des émissions de gaz à effet de serre.

Etape 4: Définition d'une situation de référence et de différentes stratégies et de leurs mesures de réduction de la consommation d'énergie primaire ou des émissions de gaz à effet de serre, et ce pour différents types de propriétaires (chapitre 3)

Etape 5: Calcul de l'effet énergétique des mesures (méthode, cf. chapitres 2.1 et 2.4)

Etape 6: Calcul de l'efficacité coûts-résultats, c.-à-d. de l'influence des mesures sur les émissions de gaz à effet de serre, la consommation d'énergie primaire et le coût du cycle de vie, et ce pour différentes stratégies (chapitre 3)

Etape 7: Comparaison de différentes mesures et stratégies (trains de mesures) et conclusions concernant des trains de mesures rentables et durables au niveau de l'enveloppe du bâtiment, du système de chauffage et de l'équipement du bâtiment lié à l'énergie (chapitre 3.7)

Etape 8: Recommandations pour les propriétaires immobiliers et les investisseurs (chapitre 4)

Les étapes 1, 2 et 3 sont décrites de manière détaillée au chapitre 2. Les paramètres de base des calculs comme les prix de l'énergie, les taux d'intérêt et d'escompte, les facteurs d'émission et d'énergie primaire ainsi que les données climatiques sont définis et présentés au chapitre 2.2.

Un bâtiment de référence pour les calculs est choisi sur base de la typologie suisse du bâtiment. Le rapport se concentre sur des maisons plurifamiliales de différentes périodes de construction. Selon la statistique des bâtiments de l'Office fédéral de la statique concernant l'année 2000, les systèmes de chauffage avec des énergies fossiles sont particulièrement significatifs. D'autres systèmes de chauffage sont étudiés dans le cadre des stratégies de rénovation.

Il y a des données techno-économiques pour les mesures de construction, de transformation et de technologie de construction visant à réduire les émissions de gaz à effet de serre et la consommation d'énergie primaire. Elles proviennent de différentes sources comme les coûts élémentaires (EAK) du CRB (enveloppe du bâtiment), Fernwärme Zürich et Amstein+Walthert (systèmes de chauffage) et Siemens (immotique). Les données techno-économiques utilisées sont présentées au chapitre 2.4.

Quatre types différents de stratégies ont été définis pour illustrer la diversité des genres de propriétaires et leurs préférences individuelles:

V. Réticent aux investissements

VI. Concentré sur l'environnement

VII. Concentré sur la technologie

VIII. Coût du cycle de vie optimisé

Chaque type de stratégie renferme des variantes supplémentaires pour tenir compte d'une sensibilité à différentes mesures. Les calculs et résultats détaillés des stratégies sont présentés au chapitre 3. Les résultats détaillés de l'application de chaque stratégie principale à la situation de référence sont résumés et comparés au chapitre 3.7. Les coûts et l'utilité marginaux de chaque mesure sont en outre représentés en fonction de la réduction des émissions des gaz à effet de serre et de la hausse de l'efficience énergétique primaire pour les différentes stratégies.

Résultats

En comparaison au scénario de référence 2, la plupart des stratégies montrent pour les premières étapes une légère tendance à la hausse des coûts en fonction de la baisse de la consommation d'énergie primaire et des émissions de gaz à effet de serre. Une courbe légèrement ascendante en fonction d'émissions de gaz à effet de serre et de consommations d'énergie primaire **plus faibles** (c-.à-d. de droite à gauche dans les figures 1 et 2) signifie que les mesures sont relativement rentables mais sont seulement presque économiques. (Des mesures économiques seraient représentées par des courbes descendantes.) Les dernières étapes dans une stratégie donnée causent cependant une pentification de la courbe dans la plupart des stratégies.

Les différentes stratégies sont présentées dans le tableau 1 de l'aperçu. Les résultats des coûts annuels comme fonction de la réduction des émissions de gaz à effet de serre et de la consommation d'énergie primaire sont présentés pour chaque stratégie dans les figures 1 et 2. Deux des stratégies atteignent complètement les valeurs cibles «Exploitation» de la SIA 2040 pour les émissions de gaz à effet de serre pour immeubles d'habitation (6 kg CO_{2eq}/m^2a), deux sont très proches et trois sont approximatives. Trois stratégies atteignent les valeurs indicatives SIA 2040 pour la consommation d'énergie primaire (450 MJ/m^2a):

- Toutes les stratégies permettent de réduire nettement les émissions de gaz à effet de serre, en général de plus de 70%. La valeur cible «Exploitation» du cahier technique (MB) SIA 2040 est atteinte par quatre stratégies (orienté image environnementale et changement climatique) ou n'est pas atteinte (orienté coût de cycle de vie avec changement climatique resp. orienté changement climatique et énergie primaire). Trois autres stratégies offrent une forte approximation de la valeur cible, en comparaison à la situation initiale. La réduction est la plus faible pour la stratégie réticente aux investissements, et atteint seulement environ 50% de la réduction maximale.
- Pour l'efficacité énergétique primaire, l'augmentation maximale est atteinte par les stratégies «orienté coûts de cycle de vie et énergie primaire», «orienté coûts de cycle de vie, changement climatique et énergie primaire» et «orienté environnement – énergie primaire», De plus, les stratégies, «orienté image environnementale» et «orienté gaz à effet de serre» atteignent la valeur cible de la SIA 2040. L'augmentation la plus faible de l'efficacité d'énergétique primaire résulte, analogue aux émissions de gaz à effet de serre, des stratégies «orienté technologie» et «réticente aux investissements».

Le deux valeurs cibles (gaz à effet de serre et PE) sont atteintes uniquement par la stratégies combinée «orienté coûts de cycle de vie, changement climatique et énergie primaire» et ce relatif à l'éfficience des coûts, lorsque les deux dernières étapes de mesure sont négligées.

En complément à la valeur cible «Exploitation», la somme des valeurs indicatives «Exploitation» et «Construction» sont indiquées dans les figures 1 et 2 (11 $kgCO_{2eq}/m^2a$ pour les émissions de gaz à effet de serre et 530 MJ/m^2a pour le PE total).

	Description	Réticent aux investissements	Orienté sur le classement éco-logique	Orienté sur l'environnement -le changement climatique	Orienté sur l'environnement -l'énergie pri-maire	Concentré sur la technologie	Orienté sur le coût du cycle de vie et le changement climatique	Orienté sur le coût du cycle de vie et l'énergie pri-maire
M 1	Isolation thermique	Etape 4 toiture isolation thermique standard	Etape 2 fenétre Minergie Step 6 Façade Minergie	Etape 3 fenétre Miner-gie-P	Etape 1 façade Miner-gie			Etape 1 façade Miner-gie-P
M 2	Système de chauffage	Etape 2 gaz	Etape 5 bois	Etape 1 bois	Etape 3 Chauffage urbain	Etape 3 Thermopompe géo	Etape 2 Thermopompe géo	Etape 2 Chauffage urbain
M 3	Système d'aération à récupération de chaleur		Etape 4		Etape 2	Etape 4		Etape 7
M 4	Applications de l'électricité (éclairage, réfrigération et autres applications)				Etape 5 Efficacité forte	Etape 2 Efficacité mi-lieu		Etape 4 Efficacité forte
M 5	Mix énergétique	Etape 1	Etape 3	Etape 2			Etape 1	
M 6	Commande et réglage de l'immotique et	Etape 3 Amélioration de C à B		Etape 4 Amélioration de C à A, juste thermal	Etape 6 Amélioration de C à A	Etape 1 Amélioration de C à B		Etape 6 Amélioration de C à A
M 7	Production d'énergie sur place		Etape 1	Etape 5	Etape 7	Etape 5		Etape 5
M 8	Conception de la construction et le choix des matériaux à faible énergie grise et les émissions de gaz à effet de serre				Etape 4			Etape 3

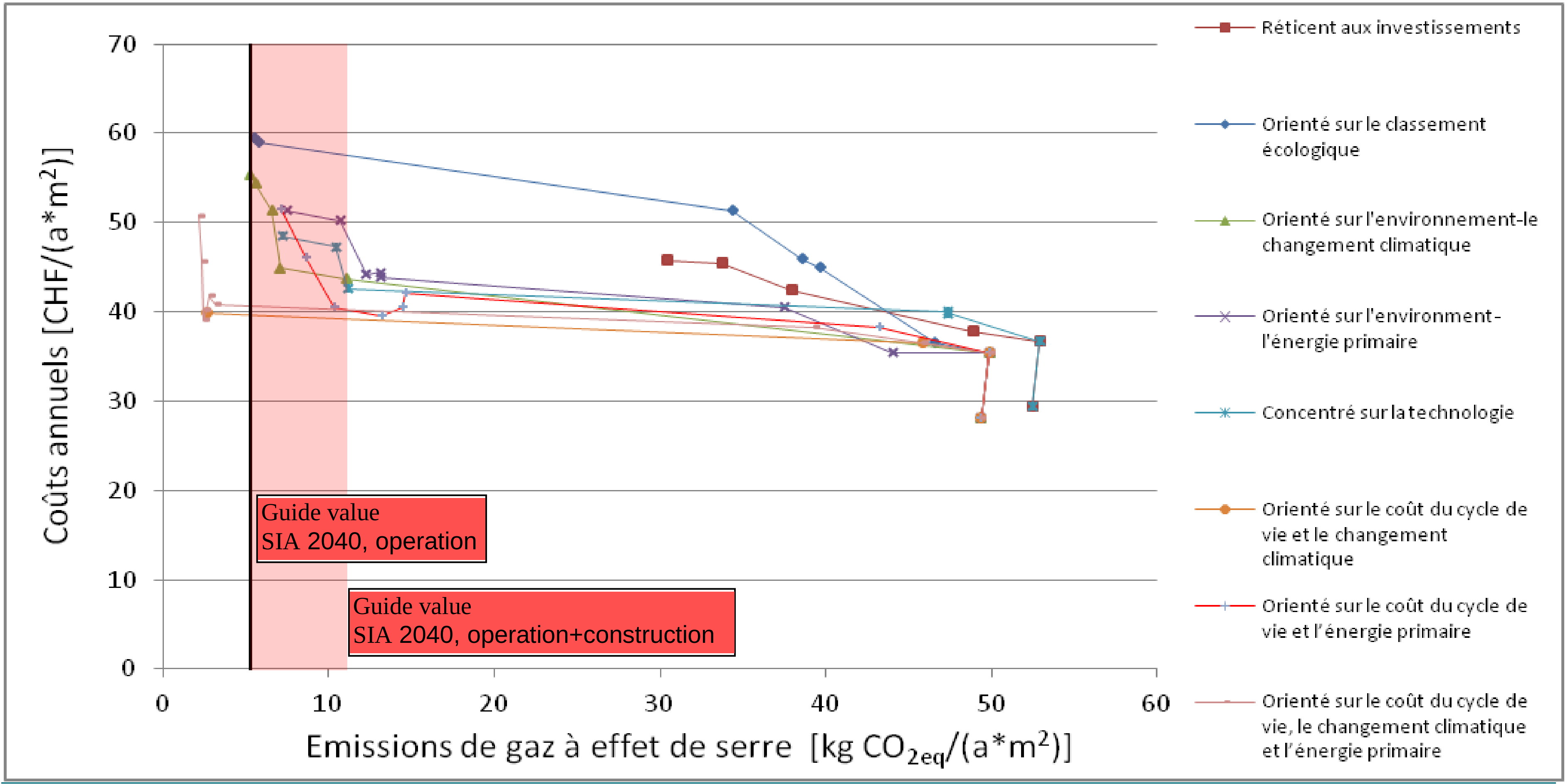


Figure 5: Coûts annuels en fonction des émissions de gaz à effet de serre pour les étapes de chaque stratégie principale (appliquée au bâtiment de référence de la période de construction 1975 – 1990) Guide value operation et operation+construction de SIA 2040 (Vernehmlassungsentwurf 2010).

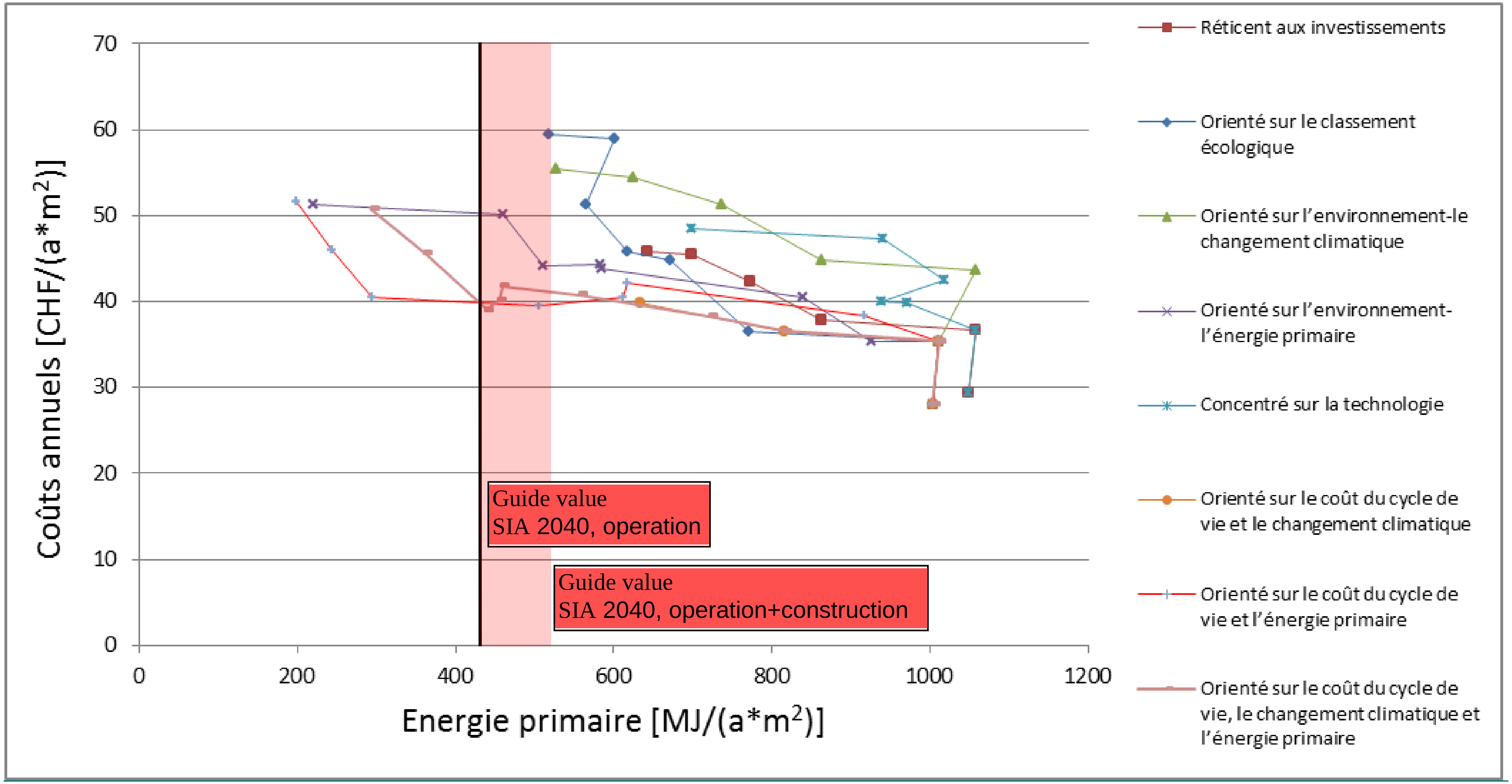


Figure 6: Coûts annuels en fonction de la consommation d'énergie primaire totale pour les étapes de chaque stratégie principale (appliquée au bâtiment de référence de la période de construction 1975 – 1990) et Guide value operation et operation+construction de SIA 2040 (Vernehmlassungsentwurf 2010).

On a réalisé deux analyses de sensibilité en complément aux calculs de différentes stratégies (cf. annexe). On a d'abord étudié la sensibilité à la période de construction. On a pris pour base la période de construction 1947-1975 au lieu de 1975-1990, qui est caractérisée de valeurs U de l'enveloppe du bâtiment plus élevée et donc un besoin de chaleur accru dans la situation de départ.

Il découle de l'analyse de sensibilité à la période de construction que les mesures d'isolation thermique sont sensibles à la période de construction en raison du degré d'isolation thermique modifié de l'enveloppe du bâtiment et du besoin de chaleur en résultant. Ces mesures ont un plus grand effet et des coûts marginaux inférieurs si elles sont appliquées à des bâtiments provenant de périodes antérieures, comme p.ex. 1947-1975. C'est dû aux valeurs U relativement élevées pouvant être améliorées à la suite de mesures d'isolation du bâtiment. Par contre, les mesures influençant un besoin en électricité ne sont pas sensibles à la période de construction.

Les résultats globaux des différentes variantes de stratégie présentent ne sont pas sensitive relative à la période de construction. Par exemple, la plupart des stratégies, qui répondent aux objectifs de la SIA 2040 de 6 kg CO_{2eq}/m^2a pour les émissions de gaz à effet de serre et 450 MJ/m^2a pour la consommation d'énergie primaire pour les bâtiments de la période 1975-1990, atteignent également ces objectifs pour la période de 1947-1975. Il faut toutefois tenir compte des exceptions suivantes: avec la stratégie «orienté gaz à effet de serre», la valeur cible relative au gaz à effet de serre n'est pas atteinte et avec les stratégies «orienté technologie» et «orienté coûts de cycle de vie et PE», les valeurs PE ne sont pas atteintes. Ceci est principalement dû à la valeur plus élevée à l'état réel.

Une autre analyse présentée en annexe étudie la sensibilité des coûts annuels à la combinaison de mesures d'une pompe de chaleur avec et sans isolation thermique de l'enveloppe du bâtiment. On observe deux cas à cet effet:

- La performance et l'efficience de la pompe de chaleur sont fixés après le montage de la pompe de chaleur. Les deux paramètres restent inchangés même en cas d'efficience accrue de l'enveloppe du bâtiment.
- La performance de la pompe de chaleur est fixée après son montage, mais l'efficience de la pompe de chaleur est changée en fonction de l'efficience de l'enveloppe du bâtiment.

Il découle de l'analyse de sensibilité décrite qu'il faut soit effectuer simultanément les investissements dans une pompe de chaleur et dans l'efficience de l'enveloppe du bâtiment ou investir d'abord dans l'enveloppe du bâtiment et ensuite dans l'installation de la pompe de chaleur, ce qui entraîne un choix correctement dimensionné de la performance de la pompe à chaleur et donc une réduction des coûts.

Recommandations

Tant le bilan que les recommandations pour les propriétaires d'immeubles et les investisseurs d'immeubles d'habitation-de maisons plurifamiliales existants sont tirés des résultats des calculs des différentes stratégies génériques de ce rapport, mais aussi des calculs dans le contexte de la partie internationale du projet INSPIRE. Les principales recommandations suivantes peuvent être formulées pour les propriétaires ou investisseurs d'une maison plurifamiliale existante (cf. également chapitre 4):

- Il est possible de suivre différentes stratégies pour atteindre des réductions des gaz à effet de serre et / ou des objectifs d'efficience énergétique primaire plus ou moins ambitieux. Quelques mesures entraînent en règle générale un effet considérable avec une rentabilité acceptable. Dans la plupart des stratégies, les «dernières» étapes sont nettement moins rentables et donc plutôt peu recommandables.
- On peut, en ce qui concerne les mesures individuelles, fixer les recommandations suivantes:
  - Les applications hautement efficaces de l'électricité (comme l'éclairage, les appareils et autres applications) sont recommandées presque sans restriction, car elles sont au moins rentables ou même économiques.
  - Les améliorations thermiques de l'enveloppe du bâtiment (isolation thermique et remplacement des fenêtres) sont rentables s'il s'agit d'un vecteur d'énergie primaire ou émettant des gaz à effet de serre et en particulier dans le cas d'une efficience encore plus faible de l'enveloppe existante du bâtiment. Par conséquent, il est recommandé de choisir soigneusement les éléments de construction à isoler et surtout de se concentrer sur les éléments encore non isolés. L'étape de Minergie vers Minergie P permet une augmentation relativement réduite de l'efficacité énergétique mais provoque des coûts limites relativement élevés. Il est donc conseillé d'investir dans d'autres mesures, comme les énergies renouvelables, le courant vert etc., car elles ont des coûts limites constants ou moins fortement croissants.
  - L'installation d'un système d'aération avec récupération de chaleur n'est pas recommandée du point de vue de la rentabilité mais d'un point de vue normatif: de tels systèmes sont à recommander si des objectifs de grande ampleur doivent être réalisés, surtout si une source d'énergie primaire et intensive en gaz à effet de serre est présente. L'inclusion d'autres avantages dans le domaine du confort d'habitation (qualité de l'air, insonorisation) et de la protection contre l'humidité peut entraîner une évaluation positive.
  - Un système de chauffage à pompe de chaleur est un choix adéquat pour réduire les émissions de gaz à effet de serre et la consommation d'énergie primaire non renouvelable, en particulier si on utilise du courant pauvre en CO_2 (certifié ou produit sur place). En principe et pour une perspective à long terme, il est aussi recommandé de rénover l'enveloppe du bâtiment avant l'installation d'une pompe

à chaleur, surtout pour les pompes à chaleur à sondes géothermiques. Ceci permet de réduire les coûts liés à la puissance (longueur de sonde et dimension d'installation). Il faut toutefois souligner, que ces économies de coûts sur la pompe à chaleur ne suffisent pas à justifier une isolation complète de l'enveloppe du bâtiment; une rénovation modérée de l'enveloppe du bâtiment est suffisante. Un système de chauffage à base de chaleur à distance entraîne en outre tant une baisse nette des émissions de gaz à effet de serre que de la consommation d'énergie primaire. Un système de chauffage au bois n'est certes pas un choix adéquat pour réduire la consommation d'énergie primaire totale mais celle d'énergie primaire non renouvelable et les émissions de gaz à effet de serre.

- Un choix adéquat de mesures d'assainissement peut, par rapport à un choix de mesures suboptimales, réduire fortement les émissions de gaz à effet de serre et la consommation d'énergie primaire, et ce pour un coût comparable du cycle de vie (cf. stratégies réticentes aux investissements et «orientées sur le coût du cycle de vie, le changement climatique et l'énergie primaire» dans les figures 1 et 2). Il est également recommandé d'évaluer la stratégie considérée avec l'outil INSPIRE.
- Etant donné les prix bas des modules PV qui permettent l'installation bon marché du PV et à condition d'une facturation nette, le PV est recommandé en raison de sa rentabilité très avantageuse (par rapport à d'autres mesures).
- Le choix de mesures d'isolation thermique au niveau de l'enveloppe du bâtiment à faible teneur en énergie grise ne réduit que faiblement les émissions de gaz à effet de serre et la consommation d'énergie primaire. Il faut toutefois en tenir compte comme critère supplémentaire surtout dans le cas des bâtiments neufs.

Il est enfin recommandé de comparer les effets de différentes combinaisons de mesures ex ante. L'outil INSPIRE s'y prête p.ex.

1 Context, background, research questions and objectives

1.1 Context

This report was established in the context of the project INPSIRE which is an international project in the framework of ERACOBUILD. This report is one of the deliverables of the Swiss contribution to INSPIRE. The goal and the scope of the nationl part is extended in order to fulfill the needs of relevant stakeholders (see impressum). Besides a financial support these stakeholders contributed with their experience to make sure realistic assumptions for the different retrofit strategies are chosen and that the measures are feasible in the real world. Most relevant deliverables and outputs of INSPIRE that might be of interest for Swiss stakeholders are:

- Synthesis report about strategies of buildings in Switzerland (this report)
- Tool to calculate energy, environmental and economic indicator of buildings and greenhouse gas mitigation and primary energy efficiency strategies
- Handbook and documentation to the tool (user manual and methodology)
- International Synthesis report
- Various articles (reviewed journals and conference contributions)

1.2 Background and research questions

The building sector accounts for a large share of global final energy consumption in Switzerland. While energy related requirements for new buildings are constantly increasing, the improvement of energy performance of the building stock constitutes a major challenge for the future. The mastering of this challenge requires the identification of cost optimal retrofit strategies to achieve maximal reduction of energy consumption and carbon emissions within building renovation.

The increasing number of building retrofits meeting the requirements of advanced building standards is an indicator for the availability and feasibility of energy-efficient technologies.

The economic effectiveness and viability of building retrofits, however, depend on many factors, e.g. scope of retrofit project, time horizon, costs of retrofit measures, including information and transaction costs, performance risks, interest rate and energy price expectations as well as user preferences. Optimal energy related retrofit strategies for typical types of buildings to achieve ambitious targets for the reduction of primary energy (PE) use and greenhouse gas (GHG) mitigation haven't emerged yet nor have been systematically analyzed.

The goal of the techno-economic assessment of energy-efficient building retrofit strategies in this study is to systematically address the following research questions:

- Regarding resulting costs, GHG emissions and PE use, what is the contribution of retrofit measures improving energy performance of building envelope on the one hand side as compared to the use of renewable energies (including ambient heat) on the other hand side?
- Accordingly, what is the relation of building retrofit measures mentioned above as compared to options in the fields of building technology, lighting and appliances?
- What is the impact on the results if embodied energy and related emissions are taken into account?
- To which extent the findings are affected if further options such as on-site energy production or the purchase of final energy with low carbon and PE content would be included in the set of options.
- What conclusions can be drawn based on these results as recommendations for building owners and investors?
- Which advises may be given to building owners, investor and – indirectily – to policy makers in order to foster efficient and effective building renovation strategies and portfolios of retrofit measures in an appropriate way?

1.3 Objectives and Scope

1.3.1 Objectives

The objective of the research carried out within the part of the INSPIRE project that is covered in this report is address the research questions mentioned above and to generate in particular the following results:

a) To estimate the impact on life-cycle costs, primary energy consumption and GHG emissions of a broad set of measures, including in particular:
   - Improvements of the thermal protection by insulation of building envelope,
   - choice of energy carrier/ change in the heating system, implementation of ventilation system with heat recovery functions,
   - more efficient electricity services,
   - choice of energy supply mix,
   - control and regulation of the energy-related building systems and applications,
   - on-site energy production of electricity,
   - optimization of construction design and material choice with low embodied PE and GHG emissions, and
   - improvement of the sun- and the over-heating protection (especially non-residential buildings)

b) Develop guidelines and specific inputs regarding retrofit strategies that are relevant for different types of buildings owners and situations, taking into account a wide range of options for retrofit measures,

c) a tool to evaluate and compare packages of renovation measures taking into account the specific characteristics of any given building in terms of building dimensions, energy performance of building before renovation and available retrofit measures. Ideally the same range of measures as mentioned above should be covered.

1.3.2 Indicators considered

Strategies and policy instruments for retrofitting buildings are evaluated using a methodology which takes into account the following indicators:

- Greenhouse gas (GHG) emissions: Direct and upstream GHG emissions (in CO_{2eq}) of energy carriers
- Total primary energy (PE) use: Direct and upstream primary energy use of energy carriers consumed as well as embodied energy use for retrofit measures.[6]
- Costs: investment costs, annual capital costs, operational and maintenance (O&M) costs, energy costs. Yearly lifecycle costs are composed of the sum of annualized capital costs (interest rates and pay-off of investment costs), O&M costs and energy costs.
- Non-renewable primary energy use: Direct and upstream non-renewable primary energy demand of energy carriers

Generally spoken these indicators are normalized to an adequate functional unit, which is the unit of heated (or conditioned) floor area. For solar thermal energy and heat from the outside used by heat pumps only the associated electricity consumption is considered for calculating their primary energy demand. Additionally embodied energy use of the units is included in the assessment.

These indicators are determined on the basis of the calculated or actual annual energy consumption in a building with typical use in order to provide the following energy services:

- maintain specific temperature conditions inside by space heating and cooling, including pumps and controls
- cover domestic hot water needs
- provide other energy services such as ventilation, lighting or appliances (white goods) and other consumer products

6 Renewable energy of ambient heat (air, water, soil) is included within the boundary conditions of total primary energy use

2 Methodology

2.1 Methodological Approach

2.1.1 Overview

The methodology focuses on residential buildings and simple office buildings without cooling needs. Methodology applied does not account for building related mobility nor for co-benefits of retrofit measures. The methodology includes embodied energy use, up-stream life cycle primary energy use for energy carriers and related carbon emissions.

The evaluation methodology is structured into the following steps

Step 1: Definition of basic parameters: Development of Interest rate and energy prices; time period of the evaluation; electricity mix (section 2.2)

Step 2: Characterization of the building stock and selection of buildings for case studies (section 2.3)

Step 3: Gathering of techno-economic data regarding primary energy and GHG mitigation measures (section 2.4).

Step 4: Definition of the reference situation and of potential measures to reduce primary energy use or GHG emissions (Chapter 3)

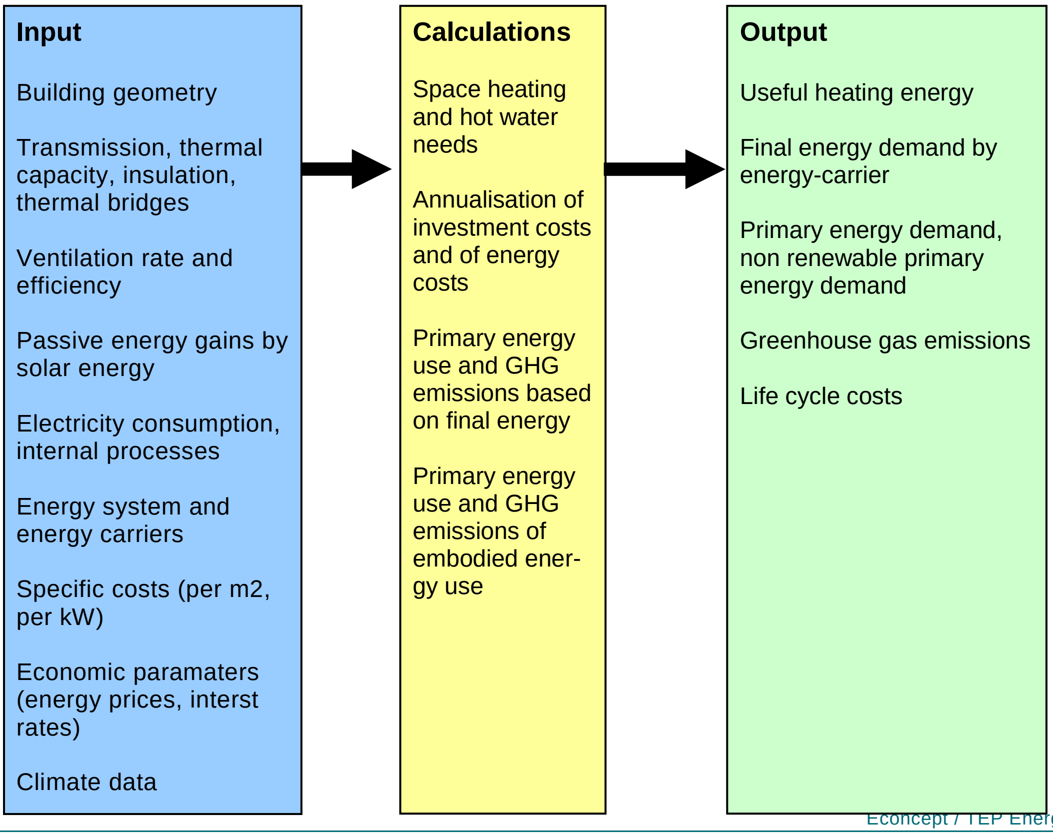
Step 5: Calculation of energy related impacts of measures (sections 2.1 and 2.4)

Step 6: Calculations of cost-effectiveness, i.e. of impact on GHG emissions, PE use and life-cycle-costs, of different measures in the context of various strategies (Chapter 3)

Step 7: Comparison of different measures and strategies (packages of measures) and conclusions concerning cost efficient and sustainable mixes of measures on the building envelope, the heating system and energy related building equipment (section 3.7)

Step 8: Recommendations for building owners and investors (Chapter 4).

A schematic representation of the methodology to calculate the environmental and economic indicators mentioned above (section 1.3) is given in Figure 7. Building data and techno-economic data of GHG mitigation and PE efficiency measures are used to calculate useful heating energy demand, final energy consumption, GHG emissions, PE use, and life-cycle-costs.



Econcept / TEP Energy

Figure 7: Simplified model representation of used methodology

2.1.2 Terminology

Within this report the following terminology is used:

— **GHG mitigation and PE efficiency measures:** any type of investment, choice or operational action that is either mitigating GHG emissions or increasing PE efficiency (or both). The following types are differentiated: (i) Construction, building and building technology related retrofit measures (ii) Appliances and lighting, and (iii) Choice of energy products such as certified electricity, biogas or district heating

— Construction measures:

— Building related retrofit measures

— Building technology measure

— Capital costs:

— Marginal costs:

— Marginal benefit:

— Cost-effectiveness

- Life-cycle-costs
- Environmental impact

2.1.3 Environmental evaluation system

Environmental impacts taken into account in this study comprise all building material and energy related greenhouse gases regulated by the Kyoto protocol of the UNFCCC. Greenhouse gases are measured in units of the global warming potential of CO_2 over a period of a hundred years (CO_2 eq). The evaluation system includes upstream emissions of energy carriers as well as life cycle emissions associated with the materials (embodied energy and related emissions).

To calculate useful heating energy, final energy consumption and ultimately GHG emissions and PE use of buildings, measures and strategies the following steps are needed:

- Energy consumption for space heating is determined on the one hand by calculating energy loss to colder environment outside due to transmission and ventilation losses and on the other hand by accounting for passive solar and internal heat gains as energy gains (for example due to lighting). Factors used in this calculation also include thermal capacity, insulation and thermal bridges. The calculations performed with country specific climate data
- The methodology for calculating useful heating needs is based on the Swiss norms SIA 380/1:2009 for calculating thermal energy use in buildings and SIA 382/2 for calculating the specific heating peak load. These norms use the same calculation principles as the standard ISO 13790:2008 "Energy performance of buildings - Calculation of energy use for space heating and cooling" and the common general framework for the calculation of energy performance of buildings according to the European Energy Performance of Buildings Directive 2010/31/EU from May 2010.
- Depending on the heating system on the efficiency of the heating system (which may depend on the building's energy efficiency) the final energy consumption by energy carrier is calculated.
- To these calculations energy use for hot water, cooling (if applicable) and electricity consumption of appliances and lighting are added.
- Greenhouse gas emissions and primary energy use are obtained by multiplying final energy consumption by specific GHG and primary energy factors (PEF) (KBOB, 2011).
- Embodied energy use[9] for retrofit measures is determined, comparing embodied energy use for building renovation with energy related measures with embodied energy use for the measures for (non-energetic) building rehabilitation in the reference case.

[9]The sources for embodied energy in building renovation: www.bauteilkatalog.ch and EMPA – ökologische Bauteile

— The unit used to compare size of buildings is the gross conditioned floor area (or simply "conditioned floor area"): The horizontal projection of that portion of space which is contained within insulated exterior walls (including the walls and insulation themselves) and which is conditioned directly or indirectly by an energy-using system.

Finally results are compared to the guide values of the technical bulletin SIA 2040 „operation“ (6 $kgCO_{2eq}/m^2a$ and 450 MJ/m^2a respectively) and „operation“+“construction“ („Betrieb“+„Erstellung“, 11 $kgCO_{2eq}/m^2a$ and 530 MJ/m^2a respectively). With this respect total primary energy use (including environmental heat) is compared consultation draft of SIA 2040 of May 2010 (SIA 2010).

2.1.4 Economic evaluation system

Cost components

For each GHG mitigation and PE efficiency measure or for packages thereof the following cost components are taken into account:

— investments

— capital costs (comprising interest and amortization) energy costs

— operational and maintenance costs

— indirect taxes (VAT)

Investments are taken into account comprehensively, comprising expenses for planning, project design, permission procedures and disposal of replaced elements.[10] However, to simplify the approach, disposal costs are not taken into account in the calculations, except for windows and for measures which typically cause extraordinary disposal costs which do not occur for alternative measures.

Costs for energy, operation and maintenance comprise the costs for all energy use and the operational costs and maintenance costs that occur during the lifetime of the building elements considered.

Categorization

In terms of GHG mitigation and PE efficiency measures the following types are differentiated:

1. Construction, building and building technology related retrofit measures
2. Appliances and lighting
3. Choice of energy products such as certified electricity, biogas or district heating

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[10] If appropriate and depending on the data availability costs of PE efficiency and GHG mitigation measures were built up bottom-up referring the costing methodology of CRB using their system eBKP-H and the “Elementartenkatalog” as a data source.

Hence, the first type of GHG mitigation and PE efficiency measures is mainly composed of construction measures. Typically GHG mitigation and PE efficiency measures are composed of several construction measures. Particularly GHG mitigation and PE efficiency measures include several cost units as defined by CRB in their system eBKP-H.

Life-cycle-costs and cost effectiveness

The life-cycle-cost and the cost-effectiveness calculations are carried out dynamically with the annuity method. In order to compare the annuity of the investment with the increasing savings of energy costs (see section below on energy prices), the savings of energy costs were discounted and then converted to an annuity. The calculations are based on real prices, real interest rates and typical lifetimes of the building elements adopted from various sources (e.g. SIA 480, SIA 2032 Graue Energie von Gebäude,, CRB: LCC Handbuch (Kennwerte zum Bauwerksunterhalt)) Often technical lifetimes are longer than the observable average life spans of real building elements since building renovation might combine various measures comprising several building elements of which not all might have arrived at the end of their lifetime. Building retrofit might also by launched before the end of the lifetime of retrofitted building elements because of changes in the building use or in the tenancy. Furthermore (professional) building owners might carry out calculations taking into account specific or risk based life spans to allow for uncertainties regarding the future use or rent potential of the building.

In other cases, however, typical lifetimes of building elements are shorter than the observed lifetime of the building. Therefore, it was assumed that such building elements will be replaced with identical elements, generating a stable annuity over the whole observation period.

Reference cases

For the economic evaluation, comparisons are carried out between packages of energy-efficiency retrofit measures applied to a building on the one hand and a **reference case** for the same building on the other hand. The reference case in general includes only overhauling measures to restore the functional use of the building after the building elements considered have reached the end of their lifetime. Overhauling measures are not carried out with the objective of improving the energy performance of the building but only for the sake of restoring functionality and replacing building elements at the end of their lifetime. Because of technological progress the reference case might also include in some energy-efficiency improvements even though the measure was not chosen to improve energy efficiency.

In the following some peculiarities of different PE efficiency and GHG measures and their reference cases are specified.

For **windows**, there are two different types of reference cases to be considered:

1. The window does not yet need to be replaced, but rehabilitation measures for example related to the painting or the sealing of the window need to be carried out. In that case the reference costs are the costs associated with such rehabilitation measures. A rehabilitated window, however, will have a shorter remaining lifetime than a new window. This is taken into account in the calculations.
2. The window is at the end of the lifespan and needs to be replaced. In that case the reference costs correspond to the investment costs for a new low-cost window that does not have an advanced energy performance yet is usually still better than the window replaced.

Because it is unclear or dependent on each individual case how the shorter remaining lifetime of a rehabilitated window compares to a new window, it is in general more adequate to take the replacement of the window with a new low-cost window as the reference case to compare with energy related measures concerning the windows. Instead the rehabilitation measures of painting or sealing can also be taken as a reference case to investigate effects of renovating windows. But in that case the cost-effectiveness of the energetic renovation measure is underestimated compared to this reference case.

For the **roof**, the reference case is distinguished as follows:
For a flat roof, the reference case is defined as rehabilitation of the roof restoring full functionality regarding weather protection but without improving energy performance. For the pitched roof, the reference case is the replacement of the roofing, yet again without improvement of energy performance.

If replacements of the **heating systems** are taken into account, the reference case is a new heating system of the same type as previously installed, taking into account an improvement of the energy efficiency due to technological progress.

Scope of cost assessment and boundary conditions

Besides reducing (non-renewable) energy consumption many energy related measures have further benefits, called co-benefits. They could be taken into account if information is available regarding the economic value of such co-benefits.

Subsidies are considered to be temporary measures to promote the distribution of certain technologies or behaviors. In this study, the main interest is to investigate cost optimal packages of measures from a societal perspective. For this reason, the calculations in this study are carried out <u>without</u> taking into account subsidies to obtain a realistic assessment of costs and resource use incurred by energy related measures.

From a societal perspective, it makes sense to take into account external costs of energy consumption. The inclusion of such external costs leads to perspectives which allow for identifying packages of measures that are optimal for society as a whole. However, the possibility of an “internalization” of related aspects into a global cost assessment framework depends on the availability of monetary data regarding external costs. A part of external costs of climate change due to carbon emissions is internalized by adding existing CO_2 taxes to the final energy prices.

VAT and mineral oil taxes on energy carriers are cost elements of the energy related measures and are also taken into account.

2.2 Framework parameters

2.2.1 Basic economic data

Energy prices

Energy prices used for the calculations in Chapter 2 are listed in Table 3. Energy prices (CHF/kWh) were derived mainly from the values published in the Swiss Energy Perspectives 2050 (BFE/Prognos 2012) with two exceptions: Wood and biogas. Prices for wood-related energy carriers (logs, chips and pellets), however, were estimated form historical and actual prices by assuming a more or less stable relation to the oil prices in the future. A similar concept was used for biogas by assuming a stable premium on top of the natural gas price.

Energy carrier	2010	2020	2030	2040	2050
Oil	0.093	0.110	0.123	0.130	0.134
Natural Gas	0.100	0.118	0.133	0.143	0.149
Wood logs	0.053	0.070	0.083	0.093	0.103
Wood chips	0.041	0.055	0.068	0.082	0.095
Wood pellets	0.085	0.102	0.116	0.124	0.128
Biogas	0.180	0.199	0.214	0.224	0.230
District heating	0.086	0.101	0.115	0.122	0.127
Electricity	0.250	0.257	0.278	0.287	0.288

Table 3: Energy prices (CHF/kWh) for households and for the tertiary sector (including taxes) used in the (BFE/Prognos 2012) and own calculations).

Discount and interest rates (both from a private and a societal perspective

Discount and interest rates are typically in the range of 2% - 6% for real estate, depending on the country and its economy. Guidelines to EPBD recast suggest to use an average real social discount rate of 4% per year (Official Journal of EU, 19.4. 2012, p. C 115/18). A higher discount rate (4 - 6%) is attributed to a private, investor or commercial short term perspective. A lower real discount rate of 2 - 4% is attributed to a social perspective (climate policy, building occupants, policy for sustainability). Private discount and interest rates are usually higher because of higher time preference or risk aversion of private persons and often because of higher risks of private investments. Due to long life cycles typical for buildings it is appropriate to adopt a best guess for average future real interest rates during the life cycle of the building.

Hence, real discount and interest rate assumed for (societal) cost assessment is **3% per year**.

2.2.2 Emission factors and primary energy factors

Emission factors and primary energy factors used refer to greenhouse gas emissions or primary energy use of energy carriers consumed including upstream emissions associated with the production, transport and delivery of these energy carriers. Emissions from CH_4 and N_2O are converted into CO_2 equivalents using the UNFCCC global warming potentials of 21 for CH_4 and 310 for N_2O. Electricity mixes are either based on primary energy input structure or on the electricity "products" as demanded by the market, and not the national production. The emission factors and primary energy factors used in this project for the countries involved are indicated in Table 4.

	GHG Emission factor	Primary non-renewable energy factor	Total primary energy factor
Final energy carrier	kg CO_2 eq / MJ		
Oil	0.083	1.23	1.24
Natural gas	0.066	1.12	1.12
Wood logs	0.004	0.05	1.06
Wood chips	0.003	0.06	1.14
Wood pellets	0.01	0.21	1.22
Country mix for electricity	0.042	2.63	3.05
Certified electricity	0.004	0.03	1.24
Zurich district heating mix	0.02	0.37	0.62
Country mix for district heating	-	-	-

Table 4: Greenhouse gas emission factors and primary energy factors used in calculations. The table contains empty cells, as only data actually used for calculations is indicated. (KBOB, 2011)

2.2.3 Climate data

For calculating temperature differences between the interior of the building and the outside, monthly average temperatures are required as an input into the ISO 13790: 2008 calculation tool. Furthermore, monthly average global radiation from East, West, South and North is needed in MJ/m^2. Climate conditions are assumed to be constant over time.

2.3 Building typology and selected building type for generic calculations

The total number of the single family residential buildings is 945‘110 and for multi-family constructions it is equal to 419‘723 according to the Swiss statistics of 2010. The total number of dwellings for SFH is estimated to 1‘080 812 and for MFH is 2‘998‘248 (GWS2010).

Construction period	SFH [Tsd m^2]	MFH [Tsd m^2]	SFH+MFH [Tsd m^2]
-1946	39 625	74 863	114 488
1946-1970	28 397	88 859	117 256
1971-1980	19 038	51 196	70 234
1981-1990	21 918	38 591	60 509
1991-2000	2 015	39 060	59 210
2001-2010	21 038	37 197	58 235
Total	**132 031**	**329 766**	**479 932**

Table 5: Gross heated area of single-family houses (detached and attached buildings), multi-family houses by construction period.

Office buildings have a high relevance within the buildings of the tertiary sector (Table 6). As can be derived this table from tertiary buildings have a large share within the construction period 1946 to 1980.

Construction period	Office buildings [Tsd m^2]	School buildings [Tsd m^2]	Other buildings of the tertiary sector [Tsd m^2]	All buildings of the tertiary sector [Tsd m^2]
-1946	2 737	5 426	28 322	36 485
1946-1970	2 801	7 545	19 814	30 160
1971-1980	2 017	5 918	18 201	26 136
1981-1990	2 257	2 079	14 825	19 161
1991-2000	2 273	2 764	12 838	17 875
2001-2005	170	257	1 045	1 472
Total	**12 255**	**23 990**	**95 045**	**131 289**

Table 6: Gross heated area of the tertiary sector, by construction period,

Given the relevance of the different building types and based on the defined project scope the following building types are further addressed within this report:

— Multi-family house buildings of different construction periods

— Simple school buildings (elementary and secondary level rather than technical universities)

— Simple office buildings (rather early construction periods without existing cooling systems (possibly with existing ventilation systems)

The first mentioned building type (MFH) is in the main focus of this report. The latter two building types are dealt with sensitivity analysis.

According to the statistics of the year 2000, the most commonly used heating system in the SFH is the one fed by oil as a source. It represents the share of 51%, of the different heating systems usage, followed by wood (15%), electricity (14%) and gas (12%). For hot water production, most commonly used are the electricity with 49% and the oil with 33% of the total share. For the multi-family residential buildings, the average share of heating systems is represented by oil with 67%, and gas with 21%. For hot water was priory used oil (61%) and gas (19%). Thus, fossil based heating systems still have a relevant share in both SFH and MFH.

Fossil based heating systems are in the main focus of this report. Buildings that are currently heated with district heating, wood or heat pumps are included with sensitivity analysis as results on strategies and recommendations might deviate for these kind of buildings.

2.4 Techno-economic data

Next the most important techno-economic data of construction, building retrofit and building technology measures used to define GHG mitigation and PE efficiency measures used in the strategy calculations are presented. As outlined in earlier section these construction, building retrofit and building technology measures are composed of various (generally more than 1) cost positions as defined by CRB.

2.4.1 Investment costs of building envelope insulation measures

In this section used investment cost statements of façade insulation measures for MFH as a function of insulation thickness are documented, differentiating between compound façade and ventilated façade (e.g. having the same material)

Total façade insulation costs are increasing as a function of insulation thickness due to additional material costs and additional work needed to mount (see Figure 8). Cost increase is quite linear with increased insulation thickness, but if plotted as a function of the resulting U-value marginal costs would be increasing.

The costs levels of compound facades using rock wool and EPS respectively are quite similar, but the version with Polyurethane (PU) is considerably more expensive. Note that this type is used in specific cases where water or humidify proofed insulation materials are required, particularly in the case of walls in contact with or embedded in the ground.

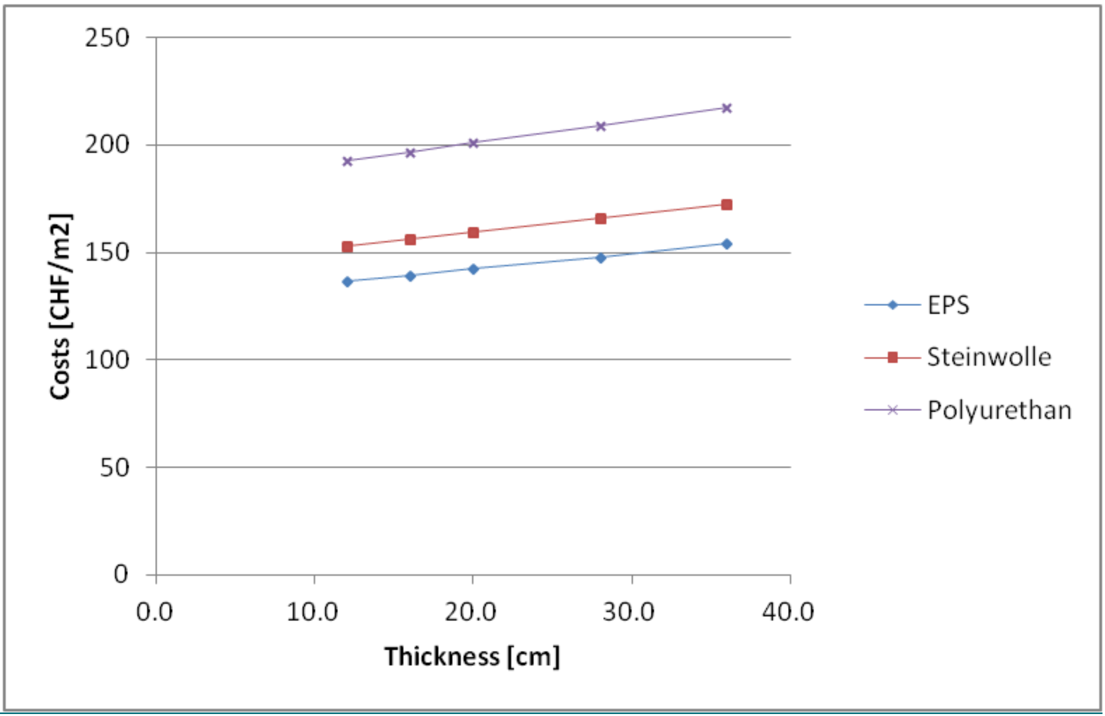

Figure 8: Investment costs of compound façade insulation measures as a function insulation thickness

The cost level of ventilated façade is usually higher as compared to the compound façade. Likewise costs are increasing as a function of insulation thickness (see Figure 9).

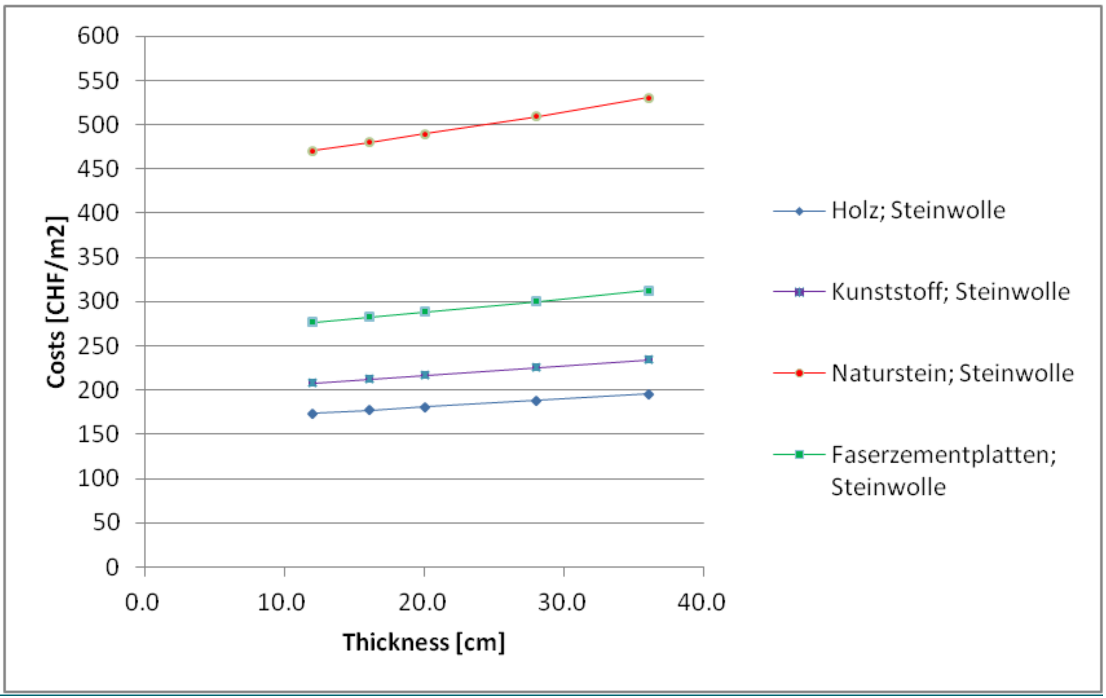

Figure 9: Investment costs of ventilated façade as a function insulation thickness

Costs of windows increase steadily with increase energy-efficiency (lower U-values), see Figure 10. The increase is more or less linear. Note that the impact of the type of window (e.g. the material of the frame) has a larger impact on the costs than the energy-efficiency has.

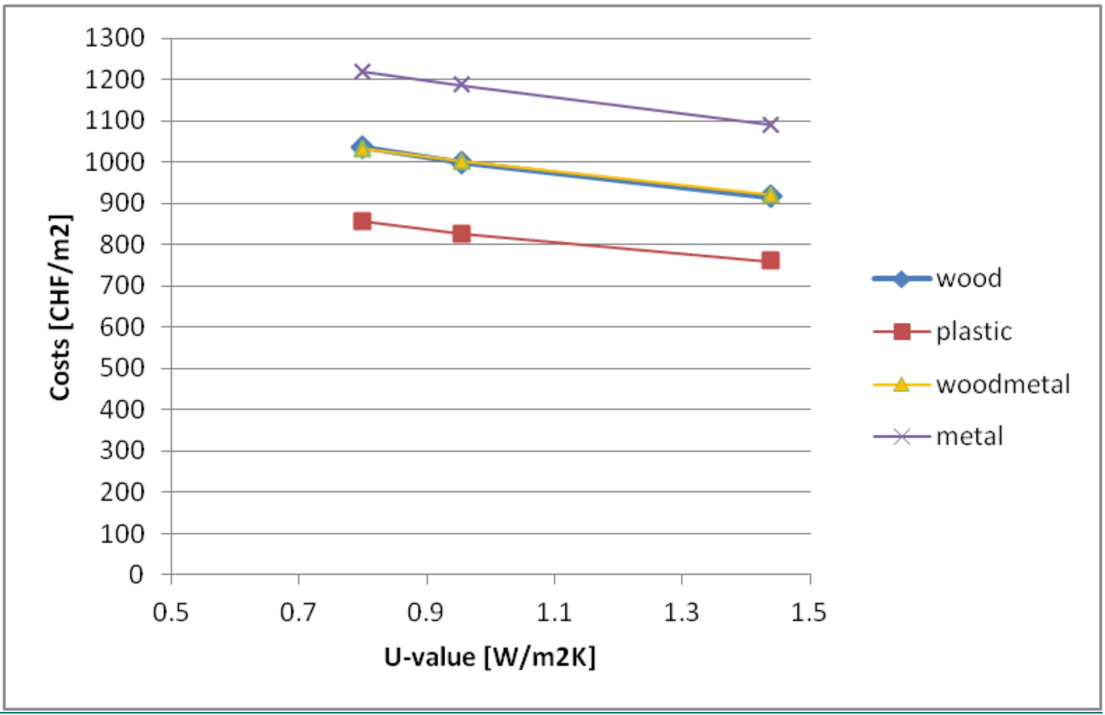

Figure 10: Investment costs of windows as a function of the window U-value. Differentiated between different frame materials.

2.4.2 Ventilation systems

Costs of ventilation systems very much depend on the type of system considered, but also on the heat recovery efficiency (see Figure 11 for two types of systems which are used in MFH) and on the electrical efficiency (specific consumption per m3/h), which in turn is influenced by the efficiency of the ventilator and its motor.

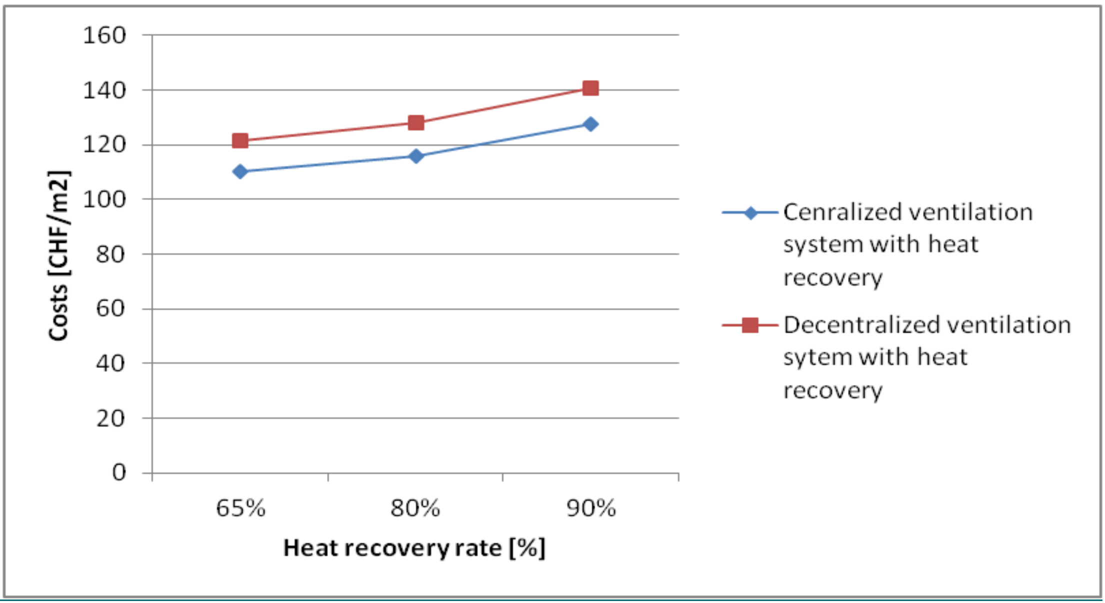

Figure 11: Investment costs of ventilation systems with heat recovery for a multifamily house as a function of heat recovery rate

2.4.3 Heating systems

Costs of heating systems are characterized by a distinct economy of scale (see Figure 12). Note that economy of scale is different across different heating systems. Hence the relative difference in terms of investment costs varies with the size of the heating system considered. As a consequence also potential cost savings resulting from buildings insulation measures that allow for installing smaller heating systems are different across different heating systems.

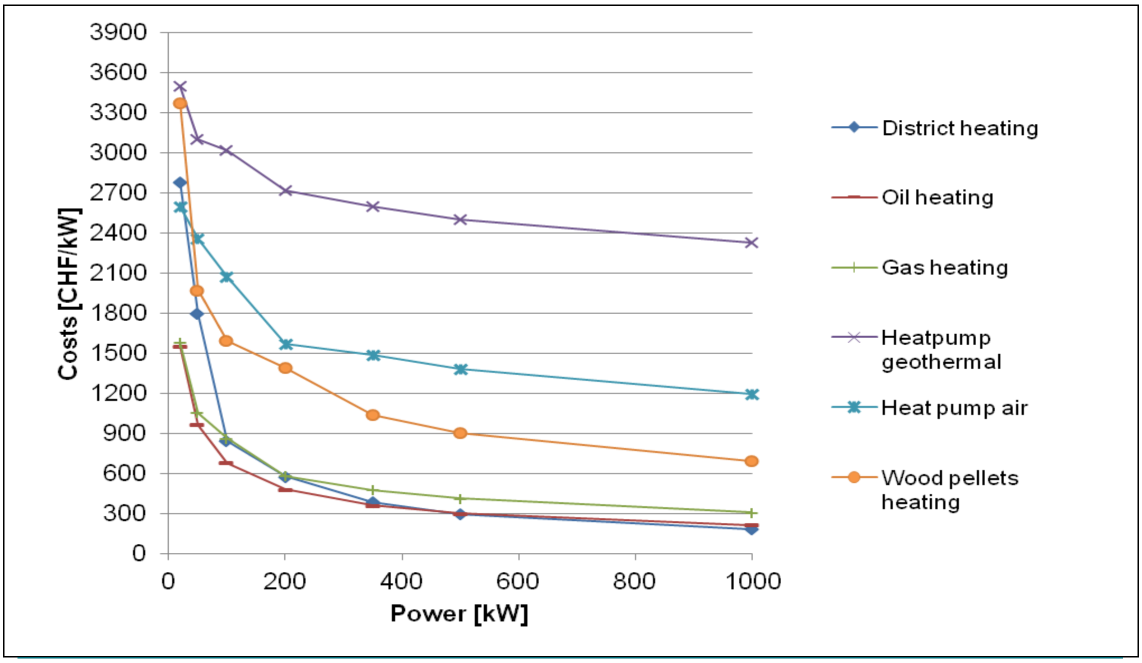

Figure 12: Investment costs[11] of different heating systems as a function of installed thermal power

Seasonal energy-efficiency factors (annual COP) of different heat pump heating systems as a function of the building efficiency are presented in Figure 13. It is assumed that heating supply temperature is affected by the building envelope insulation level. Hence, lower supply temperature of the heating distribution system would allow for higher annual COP (seasonal energy-efficiency ratio).

[11] These investment costs of the heating systems are used in the strategy calculations of this report. However, the INSPIRE tool is updated afterwards and the latest version of the investment costs is in Annex.

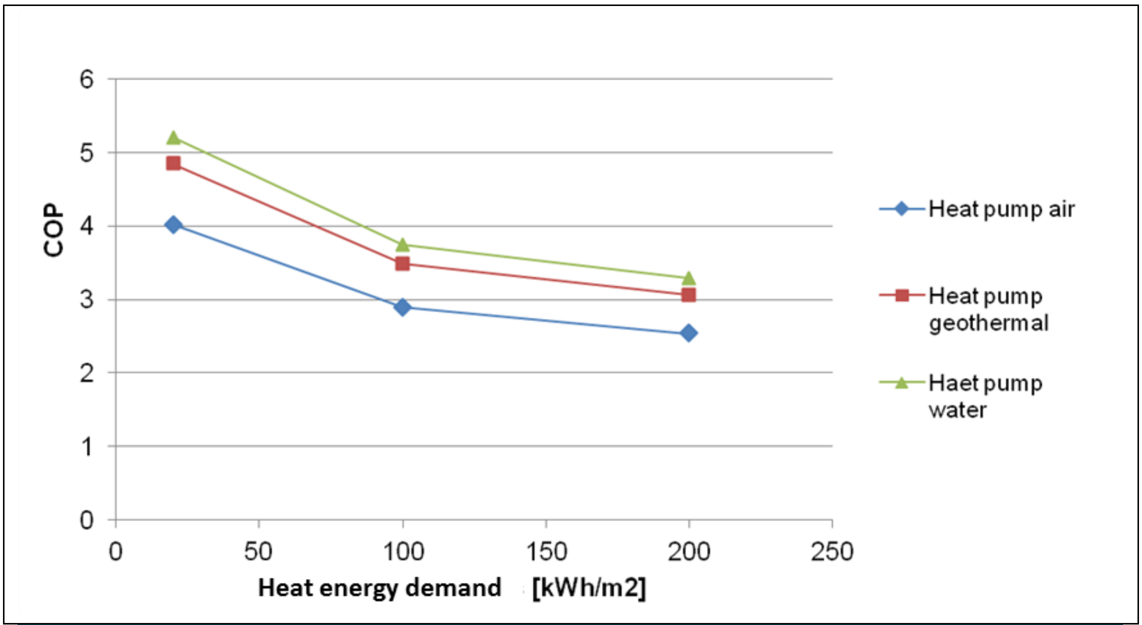

Figure 13: Seasonal energy-efficiency factor (annual COP) of heat pump heating systems as a function of the building efficiency

2.4.4 Building automation and control system

The building automation system is divided into four standard energy efficiency classes A, B, C and D. The classes are described in more details in Table 7.

Class	Energy efficiency
A	Corresponds to high energy performance building automation and control system (BACS) • Networked room automation with automatic demand control • Scheduled maintenance • Energy monitoring • Sustainable energy optimization
B	Corresponds to advanced BACS • Networked room automation without automatic demand control • Energy monitoring
C	Corresponds to standard BACS • Networked building automation of primary plants • No electronic room automation, thermostatic valves for radiators • No energy monitoring
D	Corresponds to non energy efficient BACS. Building with such systems shall be retrofitted. New buildings shall not be built with such systems • Without networked building automation functions • No electronic room automation • No energy monitoring

Table 7: Four different building automation and control efficiency classes. (Siemens, EN 15232)

The impact of different BAC energy efficiency classes on a building's energy demand is established with BAC efficiency factors. The class C is used as a reference class and the factor is 1. The impact of different BAC efficiency factors on thermal energy (heating and cooling), hot water and electricity (artificial lighting and auxiliary devices) consumption in residential building types are indicated in Table 8, Table 9 and Table 10, respectively. The classes B and A always improves a building energy efficiency.

Residential building types	Building automation and control factors thermal			
	D	C	B	A
	Non energy efficient	Standard (Reference)	Advanced energy efficiency	High energy efficiency
• Single family dwellings • Multi-family houses • Apartment houses • Other residential or residential-like buildings	1.10	1	0.88	0.81

Table 8: The building automation efficiency factors for thermal energy (heating and cooling)

Residential building types	Building automation and control factors hot water			
	D	C	B	A
	Non energy efficient	Standard (Reference)	Advanced energy efficiency	High energy efficiency
• Single family dwellings • Multi-family houses • Apartment houses • Other residential or residential-like buildings	1.11	1	0.9	0.8

Table 9: The building automation efficiency factors hot water heating energy

Residential building types	Building automation and control factors electrical			
	D	C	B	A
	Non energy efficient	Standard (Reference)	Advanced energy efficiency	High energy efficiency
• Single family dwellings • Multi-family houses • Apartment houses • Other residential or residential-like buildings	1.08	1	0.93	0.92

Table 10: The building automation efficiency factors for electrical energy

The investment costs to enhance a BAC efficiency level from C to A in the MFH are estimated roughly from the cost data received from Siemens in Table 11. One MFH is assumed to have apartments of 97 m^2 (Jakob et al., 2002). With this information an amount of rooms in a MFH is estimated. The enhancement from C to B is assumed to be 40% less expensive.

	Investment costs
Zweckbau, integrierte Raumautomation Regelung und Steuerung für Beschattung, Beleuchtung, Heizung, Kühlung und Lüftung)	3000 – 5000 CHF/room
Wohnungsbau HLK Raumautomation Regelung und Steuerung für Raumklima, Beleuchtung und Beschattung konventionell	1500 CHF/room
Beispiel Schulgebäude Integrierte Raumautomation in allen Unterrichtsräumen (Beschattung, Beleuchtung Heizung)	5000 CHF/room
Beispiel Bürogebäude Integrierte Raumautomation in allen Unterrichtsräumen (Beschattung, Beleuchtung Heizung), (25000 m^2)	72 CHF/m^2

Table 11: The building automation cost data from Siemens

2.4.5 Appliances and lighting

The main appliances considered are washing machine and dryer that are assumed to be centralized in the multifamily house. Additionally, there are small appliances within apartments. The appliances are not influenced by the building automation efficiency level. Three appliance levels (the amount of appliances) are used in the calculation. Additionally, three efficiency classes are used. The electricity consumption of medium level appliances with medium efficiency level is normalized to one. In the Table 12 the effect of each appliance and efficiency level on electricity consumption is presented.

Appliance level	Appliance efficiency level	Effect
Low	High	-36%
Low	Medium	-20%
Low	Low	-4%
Medium	High	-20%
Medium	Medium	0
Medium	Low	20%
High	High	-4%
High	Medium	20%
High	Low	44%

Table 12: The effect of the efficiency levels

The investment costs of appliances and lighting are estimated according to topten.ch and presented for washing machine and dryer in Table 13.

Appliance level	Efficiency level	Investment costs [CHF]
Washing machine	High	4200
Washing machine	Medium	3200
Washing machine	Low	2200
Washing machine and dryer	High	8800
Washing machine and dryer	Medium	6900
Washing machine and dryer	Low	5000

Table 13: The investment costs of washing machine and dryer

2.4.6 Embodied energy

An example of embodied energy content of ventilated and compound façade insulation measures with different materials are presented as a function of insulation thickness in Figure 14 and Figure 15, respectively.

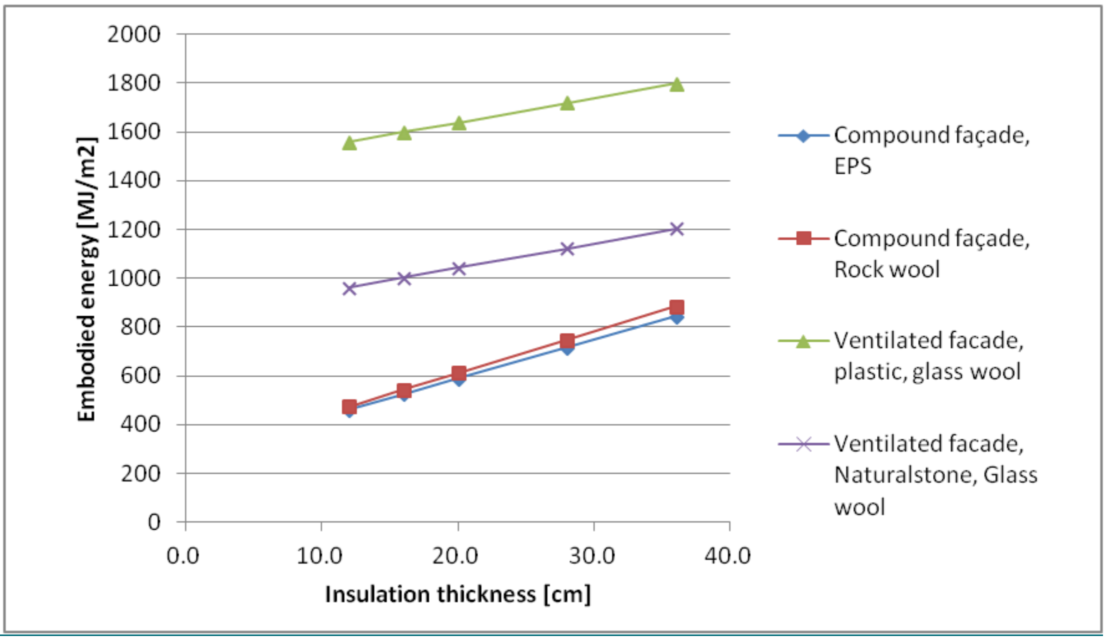

Figure 14: Embodied energy of a compound and ventilated façade insulation with different materials

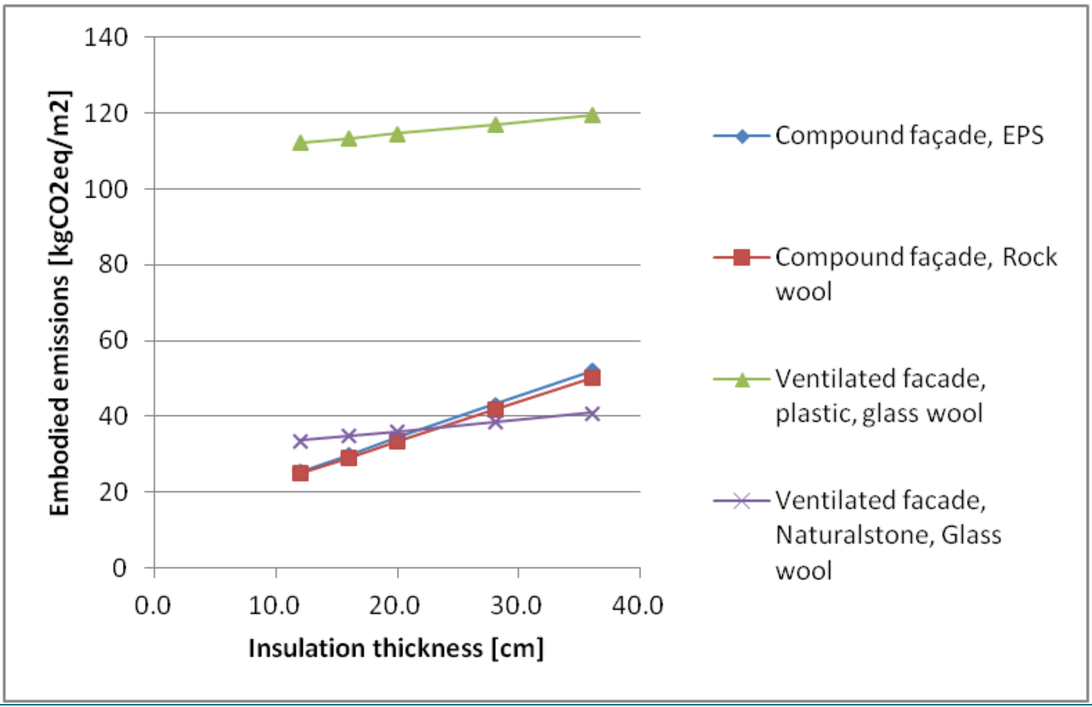

Figure 15: Embodied emissions of a compound and ventilated façade insulation with different materials

2.4.7 On-site electricity production

Two scenarios of the PV investment costs are presented in Figure 16 as a function of installed power. The costs are derived from two different sources: source 1[12] and source 2[13]. Due to technology development the investment costs have been lowered and PV (source 1) represents more realistic cost statement today. The substitution of renewable energy is not taken into account in the performed calculations in Chapter 3.

In the strategy calculations the costs of PV (source 1) are used.

[12] Dr. Ruedi Meier, Prof. Urs Muntwyler, Dr. Rosmarie Neukomm, Peter Stutz., Diskussionspapier Die Photovoltaik ist marktreif für die Schweiz. Bern, 15. November 2012

[13] BFE (2010), Photovoltaik Anlagekosten 2010 in der Schweiz

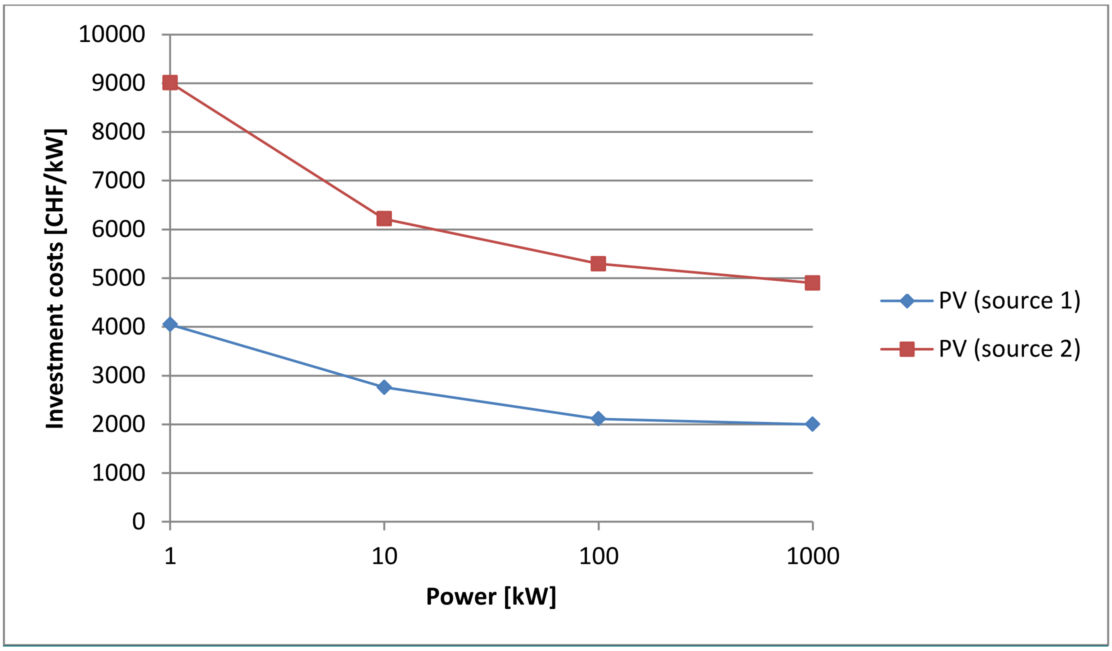

Figure 16: Two different scenarios of the investment costs of PV as a function of installed power

3 Generic assessment of retrofit strategies

In this Chapter the generic assessment of retrofit strategies is conducted. First the strategies are developed and an overview is given. Second the each strategy is implemented into the INSPIRE tool and the calculation results are analyzed. The INSPIRE tool (Jakob M., et. Al) is developed in the INSPIRE-project and based on the methodology described in Chapter 2.

In these strategy calculations total primary energy use (PE) including environmental heat used by the heat pump, GHG emissions, and yearly costs are playing the main role in the results.

3.1 Development of strategies and overview on the strategies considered

Increasing primary energy (PE) efficiency (PE use decrease) and mitigating greenhouse gas (GHG) emissions in the building sector may be achieved by different types of measures (M) which are of quite different character. To develop coherent and distinct strategies the generic measures considered within INSPIRE are classified by three different dimensions (see Table 14):

- Effect: Direct (useful) energy need (thermal or electrical) vs. GHG emissions vs. primary energy (PE) reduction
- Phase: Investment type vs. operational type
- Building element: Construction type vs. technology type

Hence, some strategies aim at reducing useful thermal or electrical energy needs others at GHG emissions reduction or yet others are rather PE efficiency oriented (or both). Some strategies adopt rather construction and investment type measures, others rather technology based ones with a stronger focus on operational measures. These aspects are considered in the process of composing different strategies (see below). Note however that a clear-cut classification is not always possible and that many measures are characterized by two or even three attributes within one dimension. For instance, insulation measures reduce useful (thermal energy) demand, and as a consequence also related PE use and GHG emissions (in general and except from barely relevant cases, primary energy use and GHG emissions are reduced too if energy needs are reduced; its ratio depend on the used heating technology and energy mix).

We distinguish between nine strategic intervention points (SIP), also called measure types (M), see Table 14, having the following effects:

- M 1: The improvement of the thermal protection by insulation of building envelope effects in a reduction of the useful (thermal) energy demand and thus in a reduction of final energy demand and related GHG emissions and PE use. In relative terms GHG and PE are reduced similarly, but depending on the type of heating technology and energy carrier either GHG or PE use are affected more.

- M 2 The choice of the energy carrier and/or the change in the heating system barely changes useful and final energy demand, but mainly reduced GHG emissions. Yet PE use is less affected, especially if total PE (including environmental heat) is considered.
- M 3 The implementation of a ventilation system with heat recovery yields in a similar effect as insulation measures (reduction of useful (thermal) energy demand, yet at the price of additional electricity consumption. Thus, as compared to insulation measures, PE use is reduced less.
- M 4 More efficient electricity services (such as lighting, cooling, appliances) mainly yield in PE reduction, especially if electricity has a low GHG content.
- M 5 The choice of the energy supply mix (electricity, district heating) does not decrease useful energy demand, it reduces mainly PE (and GHG, depending on its carbon content).
- M 6 Control and regulation of the energy-related building systems and applications may decrease both useful thermal and electrical energy demand, depending on the type of control measure considered. Thus GHG emissions and/or PE may be reduced.
- M 7 The on-site energy production, either in terms of the implementation of solar thermal panels, PV sets or small wind turbines, reduce either thermal energy demand (thus having a similar effect as thermal insulation, see M1) or electricity demand, thus resulting in a similar effect as M4.
- M 8 Construction design and material choice with low embodied PE and GHG emissions affect both PE use and/or GHG emissions, strongly depending on concrete measure considered.
- M 9 Improvement of the sun- and the overheating protection (especially non-residential buildings) reduces thermal (cold) energy demand and, as cooling is mostly electrically based, electricity demand, thus having a similar effect as M4.

	Description	Effect: Energy need / PE / GHG reduction	Phase: Investment / Operational type	Technology type: Construction / Building technology
M 1	Improvements of the thermal protection by insulation of building envelope	Energy need (thermal) => GHG / PE	Investment	Construction
M 2	Choice of energy carrier/ Change in the heating system	Type of final energy => GHG (PE)	Investment / Operational	Technology
M 3	Implementation of ventilation system with heat recovery functions	Energy need (thermal) => GHG (PE)	Investment / Operational	Technology
M 4	More efficient electricity services (such as lighting, cooling, appliances)	Energy need (electrical) => PE (GHG)	Investment	Technology
M 5	Choice of energy supply mix (electricity, district heating)	PE/GHG	Operational	
M 6	Control and regulation of the energy-related building systems and applications	Energy need (electrical and thermal) => PE / GHG	Operational	Technology
M 7	On-site energy production: Implementation of solar thermal panels, PV or wind	Energy need (thermal), type of electrical => PE/GHG	Investment	Technology
M 8	Construction design and material choice with low embodied PE and GHG emissions	PE/GHG	Investment	Construction
M 9	Improvement of the sun- and the overheating protection (especially non-residential buildings)	Energy need (if cooling is used) (thermal, electrical) => PE / GHG	Investment	Technology

Table 14: Description and classification of the considered retrofit measures

In a next step the different measures at choice (see Table 14 above) are combined for different basic strategies. To reach their goals building owners have the choice to

- select only some of the measure available, depending on the type of building owner, its preferences and its goals,
- give different priority to the individual measures, i.e. select the measures in different order

Whereas some owners rather follow a low investment cost strategy others seek for least life cycle cost elements leading to cost optimality. Some owners give priority to greenhouse gas emissions whereas others rather follow a primary energy, or more generally, a resource oriented strategy. To reflect different types of owners, priority settings and goals, but also different strategy patterns observed on the market place (for instance expressed through different codes, standards and labels) the following strategy types are considered within INSPIRE:

I. Investment scrooge

II. Environmental-focused

III. Technology-focused

IV. Life-cycle cost-optimality

Within these four different types of owners and strategies a further distinction is made within the environmental friendly (II) and the cost-optimizing (IV) ones:

II. Environmental-friendly
- II.a: Rather image oriented persons
- II.b: Rather rational, considering cost-effectiveness, GHG oriented
- II.c. Rather rational, considering cost-effectiveness, resource (PE) oriented

IV. Life cycle cost optimizer
- IV.a: targeting GHG emissions reduction
- IV.b: targeting PE efficiency increase
- IV.c: targeting both PE use and GHG emissions reductions

Within the environmental-friendly type (II) the image oriented owner rather would select those measures in the first place that are visible and have a positive image in society or in his peer group. In contrast the cost-effective oriented environmental-friendly owner rather would select measures with best cost-benefit ratio to achieve his (environmental) goal.

Within the life cycle cost optimizing type (IV) the primary concern of the IV.a sub-group is to mitigate climate change, being convinced that availability of energy will not be the major future problem. The second sub-group (IV.b) would rather tend to increase primary energy efficiency, being convinced that all types of energy use have adverse effects on the environment and on society, and PE is seen as a proxy for these effects. The third sub-group is seeking to balance GHG and PE goals simultaneously.

To highlight the individual and the cumulative effect of the different measures, each step within a certain strategy is cumulatively added to the effect of the previous steps. Hence

— the individual effect can be derived from the difference between two steps and

— the cumulative effect can be derived from the difference between the step considered and the reference defined.

In the next sections these strategies are substantiated for a multi-family house building type from the construction period 1975 to 1990 (sections 3.2 to 3.7) and from the construction period 1947 to 1974 (section 5.1 in the annex) respectively.

In Table 15 each of the strategies mentioned in the previous section 3.1 is substantiated indicating which type of measure (M) is applied at which order (step). Additionally to these main strategies some strategy variants are developed in order to investigate some specific research questions and to highlight interaction effects and interdependences (see sections 3.3 to 3.6 for more details).

	Description	Investment scrooge	Image oriented	GHG oriented	PE oriented	Technology focus	LCC optimal GHG oriented	LCC optimal PE oriented	LCC optimal GHG and PE oriented
M 1	Improvements of the thermal protection by insulation of building envelope (building element and efficiency level)	Step 4 Roof insulation standard	Step 2 Windows Minergie Step 6 Façade Minergie	Step 3 Window , Minergie-P	Step 1 Façade Minergie			Step 1 Façade Minergie-P	Step 2 Façade Minergie-P
M 2	Choice of energy carrier/ Change in the heating system	Step 2 Gas	Step 5 Wood	Step 1 Wood	Step 3 DH	Step 3 HP geo	Step 2 HP geo	Step 2 DH	Step 3 HP geo
M 3	Implementation of ventilation system with heat recovery functions		Step 4		Step 2	Step 4		Step 7	Step 8
M 4	More efficient electricity services (such as lighting, cooling, appliances) from low efficiency level				Step 5 High efficiency level appliances and lighting	Step 2 Middle efficiency level appliances		Step 4 High efficiency level appliances and lighting	Step 6 High efficiency level appliances and lighting
M 5	Choice of energy supply mix (electricity)	Step 1	Step 3	Step 2			Step 1		Step 1
M 6	Control and regulation of the energy-related building systems and applications from the efficiency level C to B or A. (See explanation in section 2.4.4)	Step 3 C to B		Step 4 C to A, only thermal	Step 6 C to A	Step 1 C to B		Step 6 C to A	Step 7 C to A
M 7	On-site energy production: Implementation of solar thermal panels, PV or wind		Step 1	Step 5	Step 7	Step 5		Step 5	Step 4
M 8	Construction design and material choice with low embodied PE and GHG emissions				Step 4			Step 3	Step 5

Table 15: The summary of strategy steps of each main strategy applied to.the base case building from the construction period 1975-1990

3.2 The base case building

The base case building used in the following strategy calculations is assumed to be from the construction period 1976 – 1990 which implies that façade and roof are already insulated to a certain (low) extent (Table 16). Moreover it is assumed that windows are replaced in the second half of the 1990s. Further relevant parameters are indicated in Table 16. It is assumed that in the environmental-friendly strategies (II) and life cycle cost optimizer strategies (IV) building owners already have taken a measure of insulating the basement in the past. Due to this the U-value ceiling of cellar is about 0.2 W/(m^2*K) instead of 0.6 W/(m^2*K).

Parameter	Unit	Multifamily house Switzerland
Construction period		1975-1990
Gross heated floor area (GHFA) A_E	m^2	730
Façade area (excl. windows)	m^2	552
Roof area pitched	m^2	340
Area of windows to North	m^2	31.6
Area of windows to East	m^2	39.5
Area of windows to South	m^2	47.4
Area of windows to West	m^2	39.5
Area of ceiling of cellar	m^2	240
Average gross heated floor area per person	m^2	40
Form factor (A_{TH}/A_E)	-	1.8
Typical indoor temperature (for calculations)	°C	20
U-value façade	W/(m^2*K)	0.5
U-value roof pitched	W/(m^2*K)	0.6
U-value windows	W/(m^2*K)	1.8
G-value windows	-	0.7
U-value ceiling of cellar	W/(m^2*K)	0.6
Heating system		oil
Energy need for space heating	MJ/ m^2	395
Energy need for hot water	MJ/ m^2	75
GHG emissions	kg CO_{2eq}/(m$_2$a)	52
PE use	MJ/(m$_2$a)	1046
Electric energy	MJ/(m$_2$a)	108

Table 16: Characteristics of the base case building used in Chapter 3

In the following strategy calculations the base case building is first advanced by some repair measures on the building envelope and heating system. These measures do have no or only a minor impact on energy efficiency but may have an impact on associated embodied energy and emissions that increase GHG emissions and PE use. The base case is depicted as Base and reference case as Ref in the following figures. For example, see Figure 17.

3.3 I. "Investments scrooge"

The "investment scrooge" person is assumed to be rather investment averse and seeks to achieve cost savings and, if ever, energy improvements by the lowest possible investments. Operational measures are preferred to bulked investments. An "investment scrooge" strategy would typically include a selection of an appropriate energy mix (M5, no or few investments are needed), the renewal of the heating system (M2) adding some better controls and adjusting regulation (M6) and, if ever, opt for a selection of low-cost insulation measures (M1).

Step 1 The change of the electricity supply mix is seen as the least cost influencing measure in terms of initial investments.

Step 2 Taking into account the current situation with existing fossil based heating system, the most probable replacement would be the replacement of the oil heating system by a more efficient one or the switch to a gas or a district heating system, if available locally and if connection is offered to moderate costs (i.e. low grid connection fee and possibly construction costs partly covered by the supplier).

Step 3 Change of and additions to the controls and regulations (control panel to adjust the "heating curve" based on outdoor temperature, radiator's control valves/ thermostats).

Step 4 A single insulation measure is more likely to be carried out (for instance insulation of the attic floor, or absolutely necessary insulation measures to improve low thermal comfort) than a package of insulation measures covering the whole envelope.

Other measures such as the addition of a housing ventilation system with heat recovery, the installation of an on-site energy production system or cumbersome insulation measures such as facade insulation would rather not be chosen in an investment scrooge strategy. Also, in terms of electrical appliances, only products with "regular" efficiency would possibly be chosen in order to avoid additional up-front investment costs.

The "investment scrooge" strategy is divided into five different variants. The main strategy V0 undertakes the lowest possible upfront investments. In the other variants more expensive upfront investments are selected in order to have higher improvements of energy performance. All the strategy variants are described in Table 17. Next the results of the main strategy are presented followed by the results of the different strategy variants.

The results of the "investment scrooge" main strategy

The results regarding GHG emissions mitigation and PE efficiency increase are represented in Figure 17 and Figure 18, respectively. The two first points, at the lower right section of the figures, depict the defined base and reference case, respectively. The third point of each variant is the first step of the strategy.

The main function of the "investment scrooge" strategy is to achieve cost savings and energy improvements by the lowest possible investment costs:

Step 1 The electricity supply mix is changed from the CH-mix to the certified electricity mix including hydropower, photovoltaic, wind and biomass (similar to the Zurich EWZ mix naturpower and ökopower product). The new electricity supply mix has a lower CO_2 content and PE intensity than the CH consumption mix (ESU Services). Due to this mix-change the GHG emissions and PE use are mitigated. The costs are increased slightly because of the higher price of the certified electricity (0.311 CHF/kWh vs 0.277 CHF/kWh).

Step 2 The existing oil heating system is replaced by a gas heating system. This replacement reduces both GHG emissions and PE use due to lower CO_2 content and PE intensity of a new energy carrier, and higher heating system efficiency. However, the annual life cycle costs are increased due to upfront investment costs and higher maintenance costs (e.g. for the grid connection) that are not paid off by lower energy costs.

Step 3 The building automation level is enhanced from the level C to B in order to reduce space heating, hot water and electricity consumption. This enhancement reduces both GHG emissions and PE use due to lower total energy demand. As composed to the previous step the effect is lower in the case of GHG emissions and similar in the case of PE use. Regarding the life cycle costs there is a bit increase of 2.8 CHF/m^2 per year, which is less than in the previous step.

Step 4 A single insulation measure is conducted as an inside roof insulation. This measure decreases the space heating demand and thus, leads to GHG emissions and PE energy reduction. As in case of the previous measure the costs are slightly increased but the increase is the least of each step.

It is found that none of the strategy steps investigated is significantly cost effective. As a conclusion the highest GHG emissions and PE reduction is reached by replacing the oil heating system by the gas system. The building automation and insulation measures reduce space heating demand and thus, GHG emissions and PE reduction. The yearly costs are increased by the each step due to upfront investment costs. The savings, made by the energy improvements, do not cover the investment costs. The insulation measure is the most cost effective due to the least steep (almost flat) cost increase compared to the other steps. Changing the electricity mix (step 1) is almost as cost-effective, but has a significantly higher reduction effect, particularly regarding primary energy. The reduction effect depends significantly on CO_2 content and PE intensity of the electricity-mix.

Additionally, the strategy does not reach the SIA 2040 guide value nor for GHG emissions (6 $kgCO_{2eq}/m^2a$ for operation) either for PE (450 MJ/m^2a for operation). The guide values, that take into account also the construction (the end of the white red band), are not reached either in Figure 17 and Figure 18.

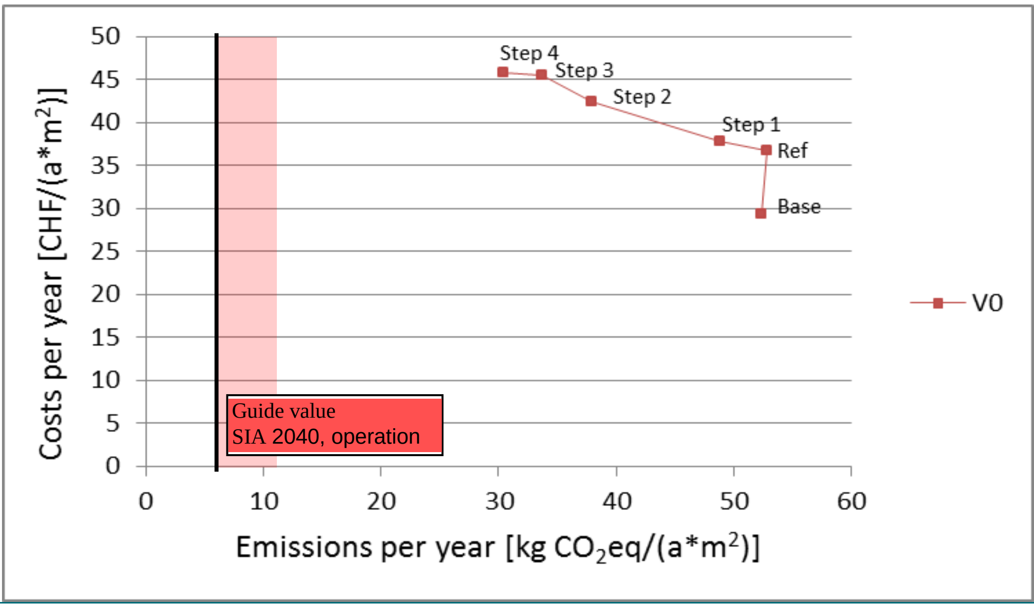

Figure 17: Yearly costs as a function of GHG emissions due to the strategy steps of the "investment scroogе" strategy compared to guide value "operation" and "operation+construction" of SIA 2040.

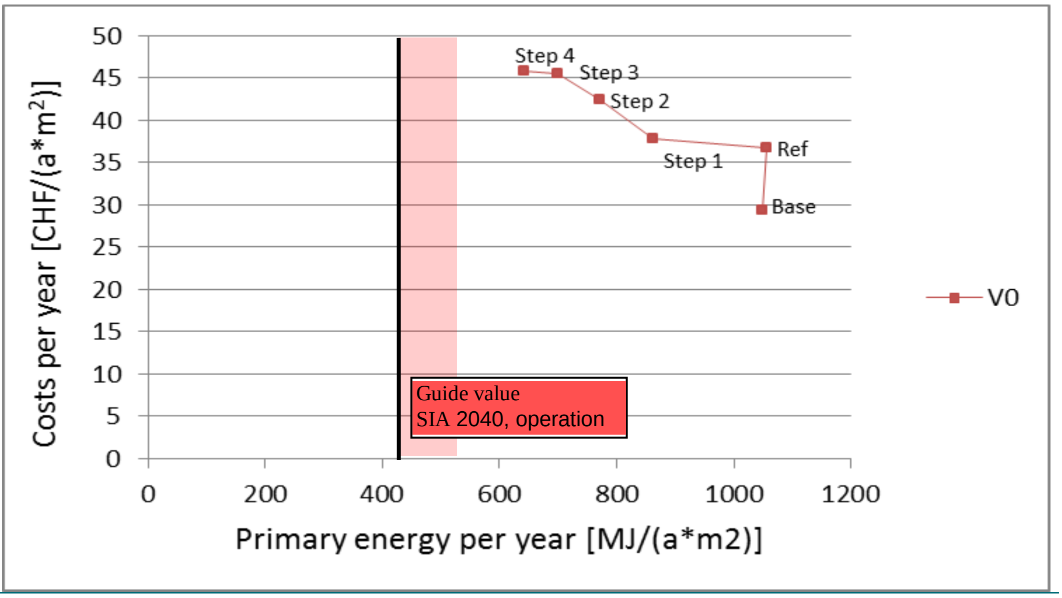

Figure 18: Yearly costs as a function PE efficiency increase due to the strategy steps of the "investment scrooge" strategy compared to guide value "operation" and "operation+construction" of SIA 2040.

In Figure 19 the life cycle costs through the main strategy are represented. The costs consist of three parts: energy, capital and operating plus maintenance costs. The energy costs are increased by the first and second steps. The second step increases energy costs due to higher energy price of gas than oil. In contrast the third and fourth steps decreases energy costs due to decreased heating demand. However, the capital costs are increased.

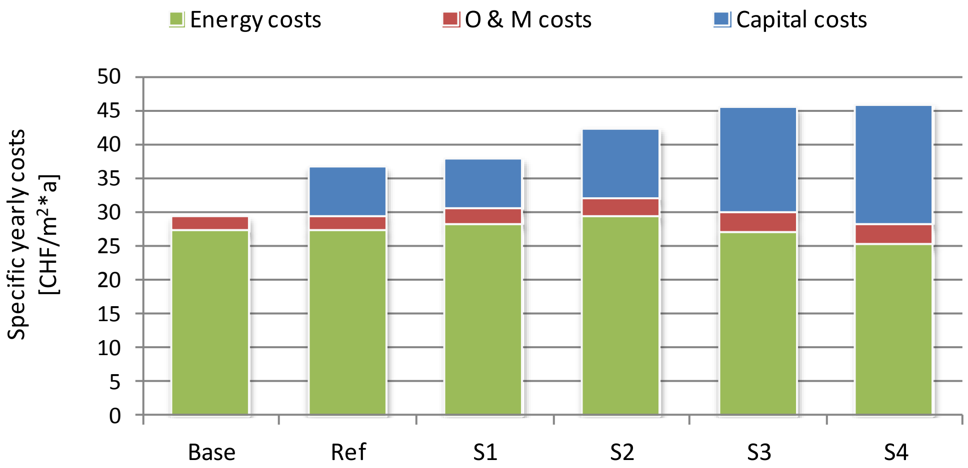

Figure 19: Specific yearly costs development depending on the steps of the strategy

The strategy variants of the “investment scrooge” strategy

In this section the main strategy, presented and discussed above, is divided into five different strategy variants. The main strategy and variants are described in Table 17. The first and second variants are similar to the main strategy except for different single insulation measures that are conducted in order to see the influence. Instead of a gas heating system a district heating system is selected in the strategy variants V3 to V5. Additionally, different single insulation measures are undertaken.

		V0	V1	V2	V3	V4	V5
		Different variants of the strategy					
Step 1	Certified electricity mix (ESU) 97.78% water, 0.83% wind, 0.73% biomass, 0.66% photovoltaic	X	X	X	X	X	X
Step 2a	Gas heating system	X	X	X			
Step 2b	District heating Zürich-mix 63% waste, 15% wood, 10% gas, 8% oil, 4% geo HP				X	X	X
Step 3	Building automation level C to B	X	X	X	X	X	X
Step 4a	Insulation standard **Roof:** Rockwool, Thickness 9.33 cm, U-value 0.25	X			X		
Step 4b	Insulation standard **Basement:** Polyurethan, Thickness 5.33 cm, U-value 0.30		X			X	
Step 4c	Insulation standard **Windows**: Wood Standard, G-value 0.75, U-value 1.31			X			X

Table 17: The steps of the main strategy and strategy variants.

The calculation results of the different strategy variants are shown in Figure 20 and Figure 21..

Below the results of different strategy variants, compared to the main strategy, are discussed.

- Instead of a gas heating system the existing oil heating system is replaced by a district heating system in the variants V3 to V5. The district heating system with Zurich mix (Variants V3 to V5) causes a higher reduction of GHG emissions and PE use due to significantly lower CO_2 content and PE factor of the district heating generation system. Due to energy savings and a slightly lower heating energy price this measure is cost-effective and the life cycle costs are much lower than in the case of the gas heating system.

- The building automation level (step 3) is enhanced the same way in each strategy variant. This efficiency enhancement reduces space heating, domestic hot water and electric energy consumption. Both GHG emissions and primary energy reduction is reached in each strategy variant when the building automation level is increased from the level C to B. However, the LCC costs are increased and the step is not cost effective. Compared to the main strategy a less GHG emissions and PE reduction is reached in the strategy variants V3 to V5. This occurs because the decreased heating demand has a higher influence to the reduction if the GHG emissions and primary energy factors of the heating energy carrier are high. This occurs if compared Zurich district heating mix and gas.

- Different single insulation measures are undertaken excluding façade insulation within the step 4a to 4c. A window replacement (step 4c in variants 2 and 5) leads to the GHG emissions and PE use reduction but the highest costs. Conversely, the inside insulation of the pitched roof or insulation of the basement results in almost no increase in the costs and decrease in GHG emissions and PE use. The insulation measures results in the higher GHG emissions and PE reductions in the strategy variants V0 to V2 compared to the V3 to V5 because of the higher GHG emissions and PE factor of the gas heating system than the district heating system.

As a summary the district heating system leads to significantly lower GHG emissions and primary energy use as compared to the gas heating system because of the lower CO_2 content and PE factor. Moreover, the building automation measure and insulation measures result in the lower GHG emissions and PE reduction with higher marginal costs if the used heating system carrier has the low GHG emissions and PE factors. The life cycle costs are the most increased with the steps 2a (gas heating system), 3 (building automation) and 4c (windows). The insulation measures of the roof or basement, especially, with gas heating and district heating system increase the costs the least steep and are the most cost effective measures.

The SIA 2040 guide value for operation and construction of GHG emissions is reached by the strategy variants in which the heating system is replaced by district heating instead of gas heating system. See Figure 20. In terms of PE use even the guide value for operation is reached in the variants with district heating. See Figure 21.

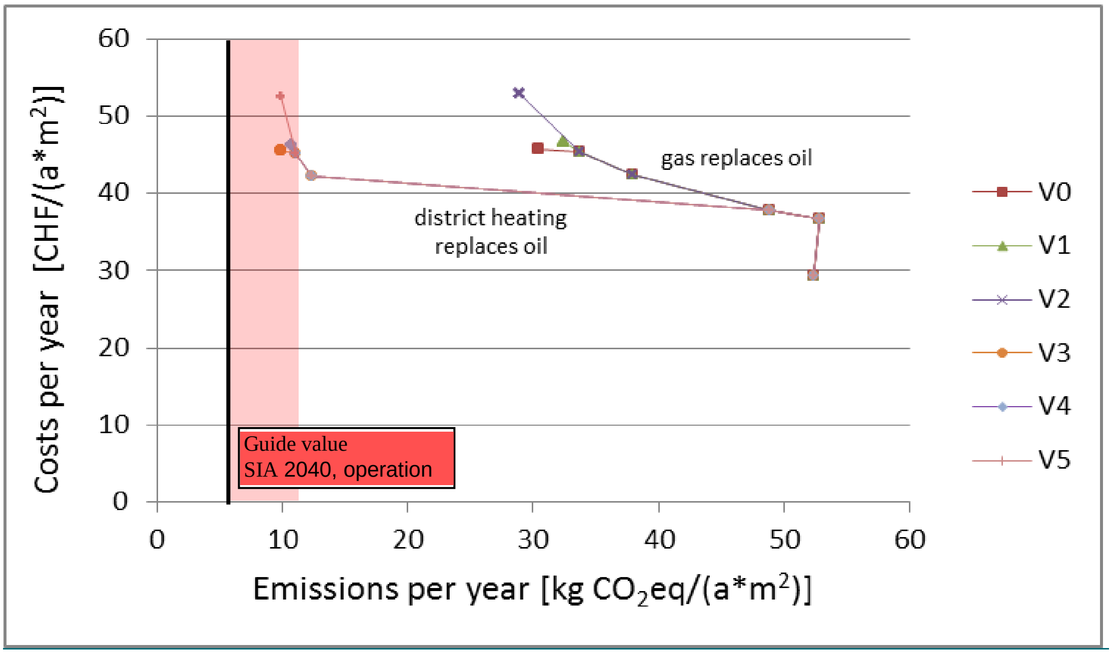

Figure 20: Yearly costs as a function of GHG emissions due to the strategy steps of the each strategy variant compared to guide value “operation” and “operation+construction” of SIA 2040.

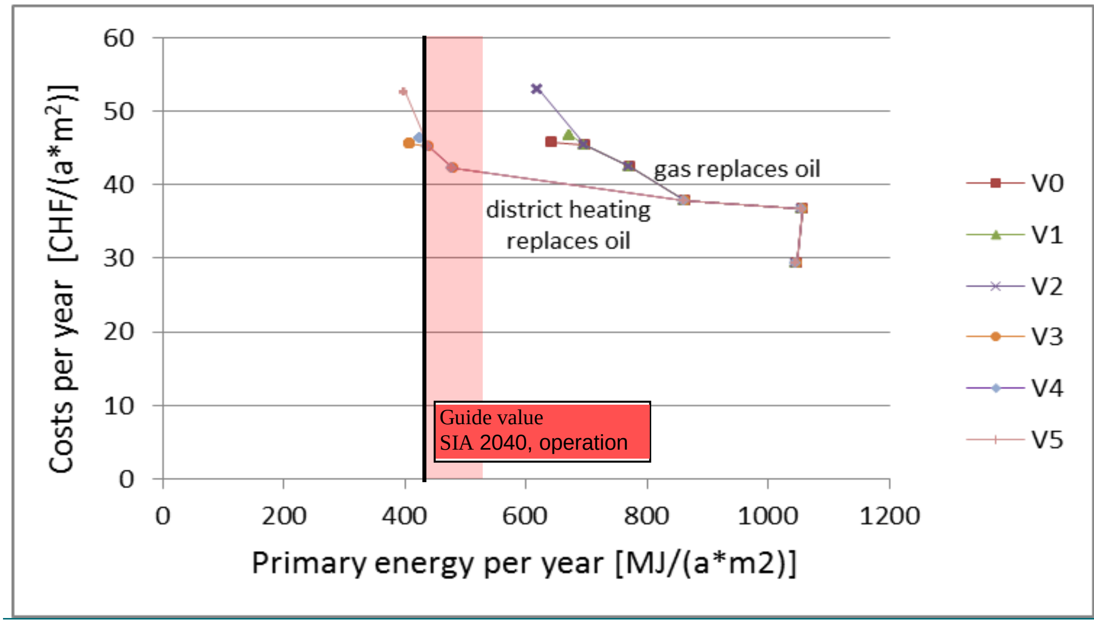

Figure 21: Yearly costs as a function of PE use due to the strategy steps of the each strategy variant compared to guide value "operation" and "operation+construction" of SIA 2040.

All in all quite significant environmental improvements may be achieved by the "investments scrooge" strategy, especially if environmental friendly district heat is available. If this is not the case GHG and PE are not reduced significantly. However, the guide values for GHG emissions and PE use according to SIA 2040 are 5 $kgCO_{2eq}/m^2a$ and 250 MJ/m^2a and these are not reached in any strategy variant of the "investments scrooge" strategy.

3.4 II. "Environment-friendly owners"

By definition in this set-up, environmental oriented "green" strategies are related to ambitious environmental goals. In such a context not all measures are necessarily economically viable (as opposed to the cost-optimal strategies (IV) more below). As outlined above three sub-strategies are considered within the environment oriented strategies:

II.a: Rather image oriented persons

II.b: Rather rational thinking, considering cost-effectiveness, GHG oriented

II.c: Rather rational thinking, considering cost-effectiveness, primary energy or resource oriented

Possibly environmental strategies are chosen by persons and owners that already have undertaken some measures in the past (typically replacing windows or insulating the basement) which means that energy consumption is already mitigated to a certain extent.

3.4.1 II.a: Rather image oriented persons

Building owners that think, decide and act rather image oriented typically would select measures that are considered by common sense as green or have a particular green reputation. Such measures are chosen for the sake of convenience ("do the right thing" without laborious search and evaluation activities), but also to portray and demonstrate the own green thinking.

Step 1 The implementation of solar thermal panels and photovoltaic cells is assumed to be a prerequisite for serving this image (M7)

Step 2 Improving of the thermal protection of the envelope is made through the replacement of the windows only (rather than using other insulation measures as well) (M1).

Step 3 Green energy is purchased to complement own on-site production (M5).

Step 4 If going one step further, an image-oriented green owner also would seek to obtain a green label such as Minergie or even Minergie-A. This makes it necessary to install a housing ventilation system (M3)

Step 5 and to change the heating system (e.g. to heat pump or wood)

Step 6 and to improve insulation to meet the requirements of the desired building label

The "image oriented" strategy is divided into three different strategy variants. The main strategy V0 and variants are described in more detail in Table 18. Subsequently, the results of the main strategy are presented first followed by the results of the different strategy variants similar as in the "investment scrooge" strategy.

The results of the "image oriented" main strategy

The results regarding GHG emissions mitigation and PE efficiency increase are represented in Figure 22 and Figure 23, respectively.

The main function of the "image oriented" strategy is to seek ambitious environmental goals even if not all measures are economically viable. The image oriented person selects measures that are considered by common sense as green or have a particular green reputation:

Step 1 The PV installation reduces both GHG emissions slightly and PE use more pronounced while the yearly costs are increased slightly due to the upfront investment costs which are, however, almost compensated by reduced costs of electricity purchase (0.277 CHF/kWh) or revenues from feed-in tariffs (0.15 CHF/kWh).

Step 2 Replacing the old windows leads to the significant reduction of GHG emissions and primary energy use because of the decreasing heating demand and because the used oil heating system has the relatively high GHG- and PE-factors. However, the costs are increased by almost 7 CHF/m^2 per year.

Step 3 The electricity supply mix is changed from the CH-mix to the certified electricity mix including hydropower, photovoltaic, wind and biomass (similar to the Zurich EWZ mix naturpower and ökopower product). The new electricity supply mix has a lower CO_2 content than the CH consumption mix (ESU Services). Due to this change the GHG emissions are mitigated. However, there is only slightly mitigation due to own electricity production, which reduces the amount of grid electricity.. Additionally, the primary energy factor is lower than in CH-mix and thus, PE use is reduced as well. The costs are increased slightly because of the higher price of the certified electricity (0.311 CHF/kWh vs. 0.277 CHF/kWh).

Step 4 The ventilation system with heat recovery reduces space heating demand and thus, reduces GHG emissions and PE energy use but only slightly due to relatively low heat recovery rate of the ventilation system (see Table 18). Yet, the yearly costs are increased significantly due to the fact that the upfront investment costs are not paid off by energy savings and due to additional operational costs.

Step 5 The replacement of the oil heating system by a wood heating system does not improve PE efficiency. The increase of PE use of the wood heating system is caused by the almost the same primary energy factor of wood than oil but the lower heating system efficiency. However, wood heating system reduces GHG emissions cost effectively due to a low GHG emissions factor. Yet, energy costs are not reduced and thus, incrementally investment costs are not paid off.

Step 6 The façade insulation measure, carried out in the case of a wood fired building, has only low impact on the GHG emissions reduction because of the low GHG emissions factor of wood and relatively high emissions from embodied energy of the insulation materials. In terms of primary energy use a more significant reduction is reached due to the relatively high PE factor and low heating system efficiency. The costs are increased only slightly (0.5 CHF/(m^2*a)) due to energy cost savings reached by the insulation measure.

As a conclusion the PV installation decreases both GHG emissions and PE use. The yearly costs are slightly increased and PV is a cost effective measure as compared to the others. The window replacement, ventilation system with heat recovery and insulation measure reduces heating demand. The extent of the GHG emissions and PE reduction depends on the GHG emissions and PE factors of the heating energy carrier and on the heating system efficiency. The strategy steps investigated are not cost effective compared to the base and reference case. However, the first (PV installation), third (electricity mix) and fifth (wood heating system) steps the most cost effective steps in terms of GHG emissions mitigation and the first, third and sixth (façade insulation) in terms of PE efficiency increase.

The strategy reaches the SIA 2040 guide value for GHG emissions (6 $kgCO_{2eq}/m^2a$ for operation). In terms of PE only the guide value for operation and construction is reached (530 MJ/m^2a for operation). See Figure 22 and Figure 23.

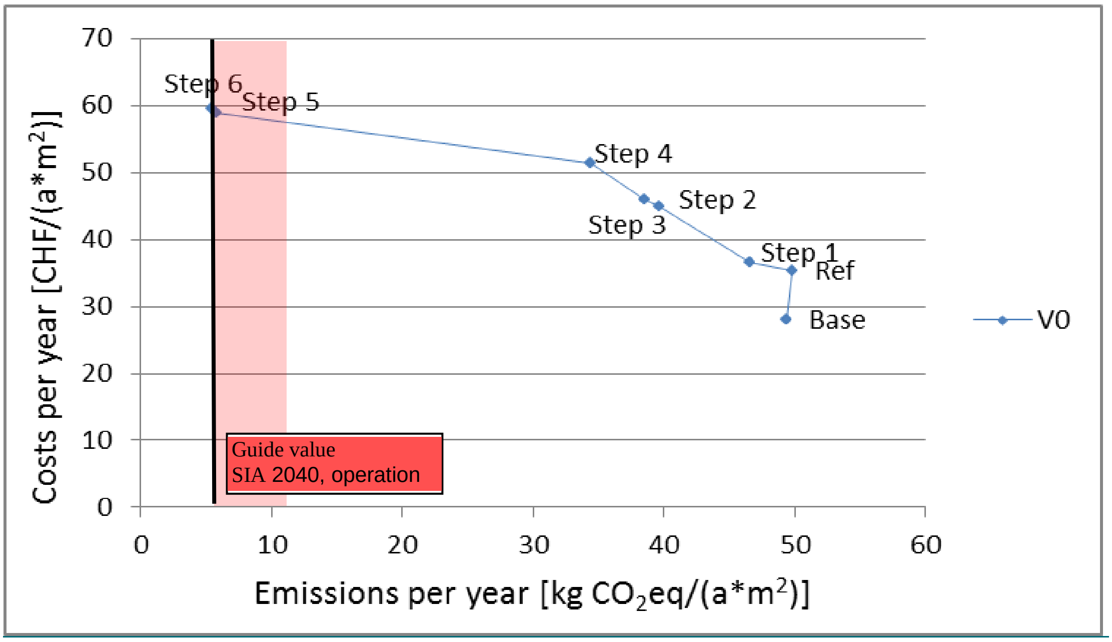

Figure 22: Yearly costs as a function of GHG emissions due to the strategy steps of the “image oriented” strategy compared to guide value “operation” and “operation+construction” of SIA 2040.

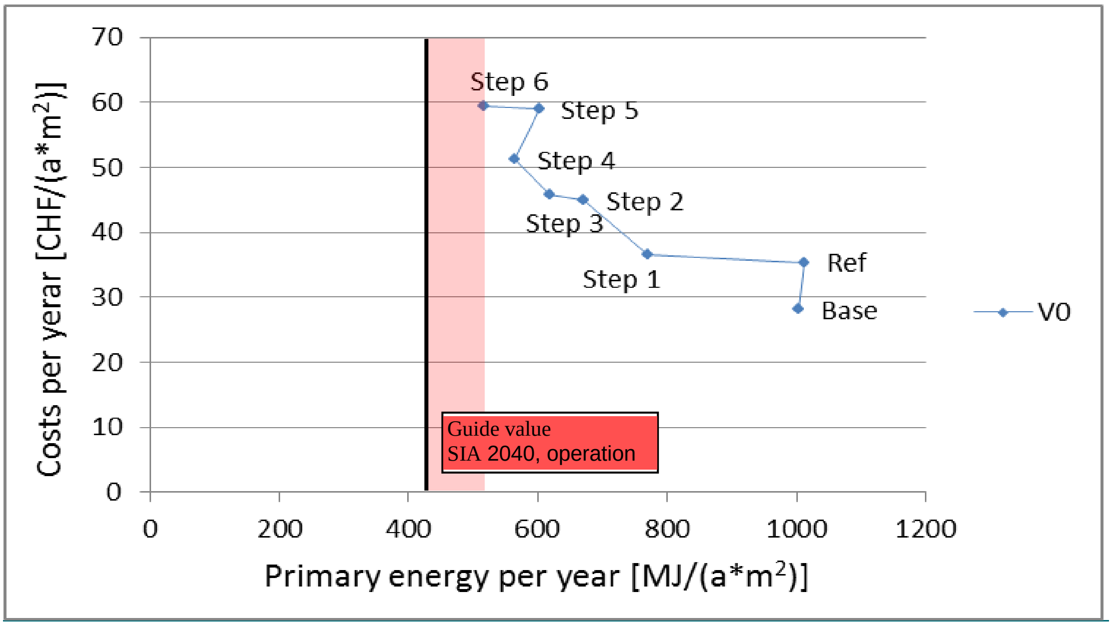

Figure 23: Yearly costs as a function PE efficiency increase due to the strategy steps of the “image oriented” strategy compared to guide value “operation” and “operation+construction” of SIA 2040.

In Figure 24 the yearly costs through the main strategy are represented. The costs consist of three parts: energy, capital and maintenance costs. The energy costs are decreased by the step 1 (PV), 2 (windows) and 6 (façade insulation). The capital costs are increased through the strategy.

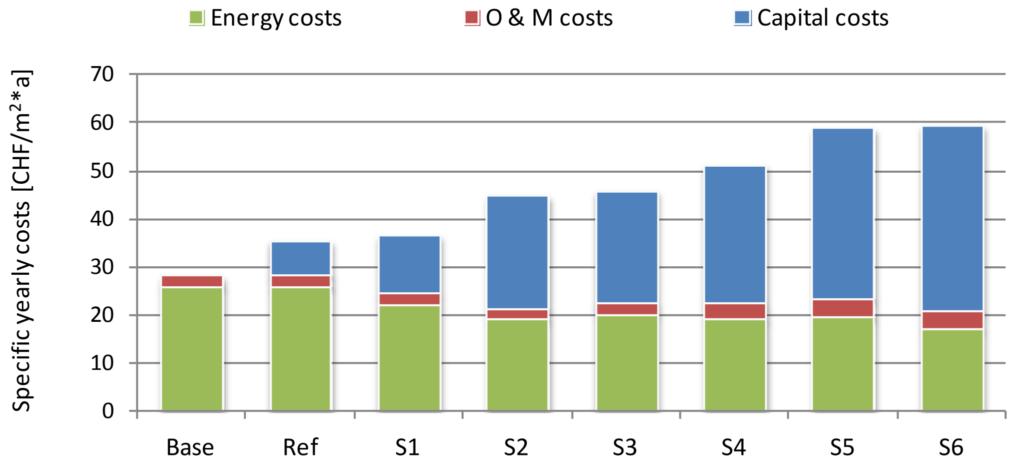

Figure 24: Specific yearly cost development depending on the steps of the strategy

The strategy variants of the "image oriented" strategy

Three different strategy variants are investigated. The most significant variant from the main strategy is within the fifth step in which the oil heating system is changed to a heat pump (the variants V2 and V3) instead of a wood heating system (V0 and V1). Each variant includes the same first and third step. Within the variants there is presented a normal image oriented person and more ambitious person. Due to this the second and sixth steps are divided into levels of Minergie and Minergie-P. Additionally, different heat recovery levels of a ventilation system are investigated within the fourth step.

		Different variants of the strategy			
		V0	V1	V2	V3
Step 1	PV P_p = 20 kW, 16000 kWh/a, 10% onsite use	X	X	X	X
Step 2a	Minergie **Windows**: Wood Standard, G-value 0.55, U-value 0.95	X		X	
Step 2b	Minergie-P **Windows**: Wood Standard, G-value 0.45, U-value 0.78		X		X
Step 3	Certified electricity mix (ESU) 97.78% water, 0.83% wind, 0.73% biomass, 0.66% photovoltaic	X	X	X	X
Step 4a	Ventilation system with heat recovery η_{el} = 0.4 η_{WRG} = 0.65 ventilated area 75%	X		X	
Step 4b	Ventilation system with heat recovery η_{el} = 0.6 η_{WRG} = 0.90 ventilated area 75%		X		X
Step 5a	Wood pellets heating system	X	X		
Step 5b	Geothermal heat pump			X	X
Step 6a	Minergie **Façade:** Rockwool, Thickness 12 cm, U-value 0.20	X		X	
Step 6b	Minergie-P **Façade:** Rockwool, Thickness 19 cm, U-value 0.15 **Roof:** Rockwool, Thickness 20 cm, U-value 0.15		X		X

Table 18: The steps of the main strategy V0 and strategy variants V1 – V3.

The calculation results of the different strategy variants are shown in Figure 25 and Figure 26, and the numeric values are indicated in Table? in Annex.

Subsequently, the results of different strategy variants are compared with the main strategy and discussed.

- Replacing the old windows (step 2) leads to a significant reduction of GHG emissions and PE use because of the decreasing heating demand and relatively high PE factors of the oil heating energy carrier. However, the difference in the reduction from Minergie to Minergie-P is almost negligible. The U-value of Minergie-P windows is lower than the one of Minergie windows. However, the G-value is also reduced which leads to lower solar gains through the windows and increasing heating demand. The Minergie-P windows increase the yearly costs slightly more compared to the Minergie windows due to slightly higher upfront investment costs and a bit higher heating demand caused by the lower G-value.

- The influence of two different heat recovery ventilation systems is investigated in the fourth step. The better heat recovery efficiency of the ventilation system leads to a slightly higher GHG emissions mitigation and PE use due to higher heating demand reduction. However, the yearly costs are increased due to the higher up-front investment costs of the more efficient system.

- Instead of the wood heating system the oil heating system is replaced by a heat pump in the strategy variants V2 and V3. This leads to slightly higher reduction in GHG emissions with the lower yearly costs as compared to the replacement by the wood heating system. The lower costs are mainly caused by the relatively high reduction of energy costs. The high GHG emissions and PE reductions occur due to the relatively low GHG emissions factor of the certified electricity mix and high overall efficiency of the heat pump.

- Compared to the main strategy the advanced insulation (step 6b) in the strategy variant V1 decreases only slightly GHG emissions due to low GHG emissions factor of wood and emissions are already low. As a matter of fact GHG emissions reduction is almost not visible (see Figure 25). In terms of PE use the reduction is more significant due to decreased heating demand and the relatively high PE factor of wood. The lower overall efficiency leads to the more significant reduction when space heating demand is reduced by the insulation measure. In the strategy variants V2 and V3 GHG emissions are even increased due to embodied emissions of the insulation materials, the significantly lower GHG emissions factor of the certified electricity mix and high heating system efficiency. Due to the high heating system efficiency of the heat pump, certified electricity mix and embodied energy of the insulation materials the insulation measures do not cause PE reduction in the strategy variants V2 and V3. In the variants V0 and V1 the LCC are only slightly increased due to energy savings caused by the insulation measures.

As a summary the measures, such as window replacement, envelope insulation and ventilation system with heat recovery, reduce heating demand. Thus, these measures have a high influence on GHG emissions and PE reduction if the heating system energy carrier has high GHG emissions and primary energy factors, and the overall efficiency of the heating system is low. In case of low factors and high heating system efficiency the measures, which reduce heating demand, can yield even negative result because of the embodied energy and the emissions of materials. The certified electricity mix reduces both GHG emissions and PE use. Both the wood heating system and the heat pump with the certified electricity mix reduce effectively GHG emissions due to a low GHG emissions factor. However, the wood heating system increases primary energy use due to the significantly lower overall efficiency than the heat pump.

The most cost effective measures in terms of the life cycle costs is the selection of a PV installation (step 1), a heat pump (step 5b) and to conduct insulation of the building envelope (step 6b) if the heating system has a lower efficiency or energy carrier with high PE and/or GHG intensity is used.

The guide values of SIA 2040 for operation (6 $kgCO_{2eq}/m^2a$ and 450 MJ/m^2a) are reached in each variant in terms of GHG emissions and in variants from V1 to V3 in terms of PE. See Figure 25 and Figure 26.

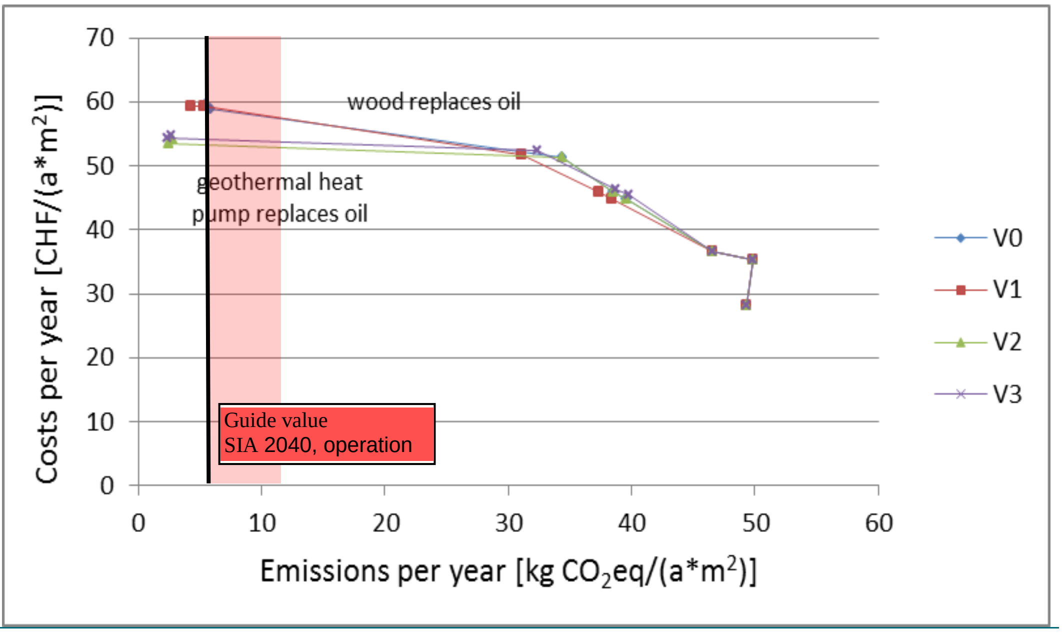

Figure 25: Yearly costs as a function of GHG emissions due to the strategy steps of the each strategy variant compared to guide value "operation" and "operation+construction" of SIA 2040.

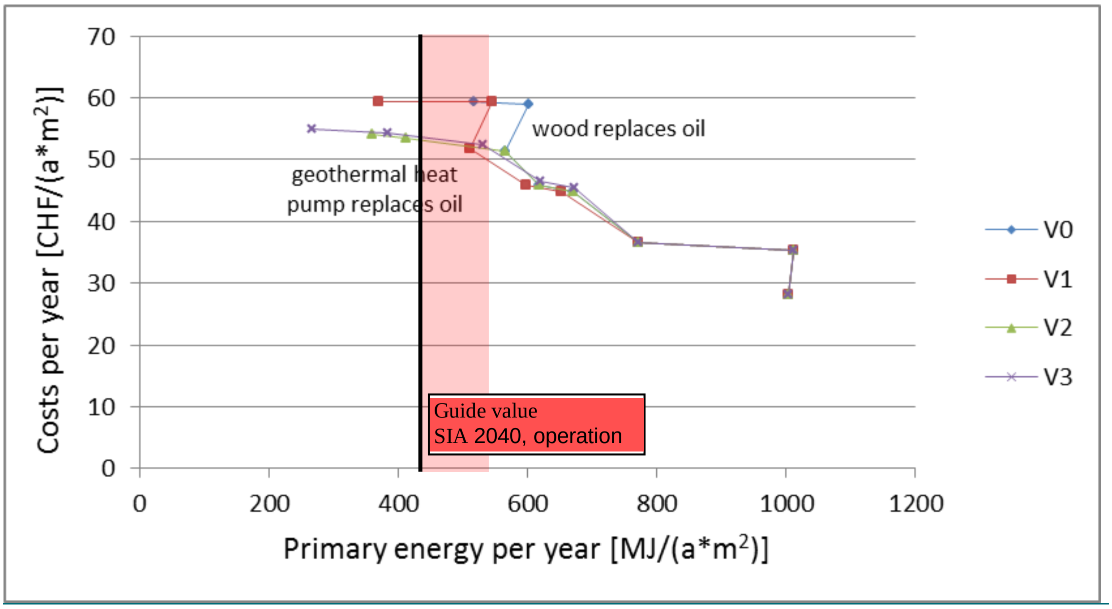

Figure 26: Yearly costs as a function of PE use due to the strategy steps of the each strategy variant compared to guide value "operation" and "operation+construction" of SIA 2040.

3.4.2 II.b: Rather rational, considering cost-effectiveness, GHG oriented

Rather than focussing on the "visibility" of her or his action the green rational person would consider the effectiveness and the cost-effectiveness of the different measures and their down-stream implications. The GHG oriented green person is convinced that emissions are mitigated most effectively by adopting a technology perspective. More specifically, GHG emissions are mitigated through renewing the existing heating system with a more efficient one, considering also the associated energy carriers including renewable energy sources. Such a strategy also leads to a significant decrease in the running energy costs, especially if renewable energy sources are associated.

Step 1 An adequate choice of a low-carbon heating system such as heat pumps, wood or district heating is seen as more rational and cost-effective than, for instance, extensive insulation or the implementation of solar panels.

Step 2 In order to reduce emissions to the maximum possible extent certified electricity and/or, if applicable, low-carbon district heating products are chosen.

Step 3 In principle, by using heat pumps and low-carbon electricity, far-reaching GHG emission mitigation goals are achieved, making further measures (seemingly) obsolete. Nevertheless, further measures are considered, both to reduce indirect emissions (e.g. in the case of district heating systems) and direct energy cost expenditures. To do so, some but not all insulation measures are adopted (e.g. attic floor and windows) (M1).

Step 4 Additionally (thermal) energy use is mitigated by building automation, controls and regulation measures (M6).

Step 5 Possibly, in a further step on-site energy production is considered (M7), also to be secure and back-up the purchase of certified electricity which might be considered as being consequent and sustainable enough.

The "GHG oriented" strategy is divided into three different variants. The main strategy V0 and variants are described more detailed in Table 19. Subsequently the results of the main strategy are presented first, followed by the results of the different strategy variants similar to the previous strategies.

The results of the "GHG oriented" main strategy

The results regarding GHG emissions mitigation and PE efficiency increase are represented in Figure 27 and Figure 28 respectively.

The main function of the "GHG oriented" strategy is to achieve ambitious environmental goals even if not all measures are economically viable. The GHG oriented person considers the effectiveness and the cost-effectiveness of the different measures and concentrates to reduce GHG emissions:

Step 1 In terms of greenhouse gas emissions the replacement of the oil heating system by a wood heating system is almost cost effective compared to the base and reference case. The yearly costs are increased by about 9 CHF/m^2 because wood energy costs are not significantly lower than oil energy costs. Therefore, incremental investment costs are not paid off. However, in terms of primary energy use a wood heating system even increases the demand and does not improve PE efficiency. This increase is caused by the only slightly lower PE factor and the lower overall efficiency of the wood heating system.

Step 2 The electricity supply mix is changed from the CH-mix to the certified electricity mix including hydropower, photovoltaic, wind and biomass (similar to the Zurich EWZ mix naturpower and ökopower product). The new electricity supply mix has a lower CO_2 content than the CH consumption mix (ESU Services). Due to this change the GHG emissions are mitigated. Additionally, the primary energy factor is lower than in the CH-mix and thus, PE use is reduced significantly. The costs are increased slightly because of the higher price of the certified electricity (0.311 CHF/kWh vs. 0.277 CHF/kWh).

Step 3 Replacing the old windows leads to a more significant reduction of PE use than of GHG emissions by the decreasing heating demand in the case of the wood heating system which has a relatively high PE factor and low GHG emissions factor. However, the yearly costs are increased by almost 6 CHF/m^2 per year due to energy cost savings that are lower than the upfront investment costs.

Step 4 The heating specific building automation enhancement from level C to A reduces heating and hot water demand. Due to the same reason as in the third step the enhancement has a higher impact on PE energy use than on GHG emissions. However, the yearly costs are increased again.

Step 5 The PV installation does not reduce significantly GHG emissions because of the used certified electricity mix from the step 2, which has a remarkably low GHG emissions factor. However, the mix has a higher primary energy factor and the installation influences more significantly primary energy consumption. The yearly costs are only slightly increased due to upfront investment costs which are almost paid off by energy cost savings. The PV installation is cost effective measure due to the least steepness of the slope.

A replacement of oil with a wood heating system decreases GHG emissions effectively, but increases PE use and PE efficiency is not improved. This is due to the following reasons: Wood has a relatively high PE factor and a significantly low GHG emissions factor and the heating system efficiency is lower than the one of an oil heating system.

Regarding further measures such as a window replacement and building automation enhancement it can be stated that heating demand and hence, PE use is reduced more significantly. Note that the yearly costs increase with each step. In terms of PE efficiency, the most cost effective steps are to change the electricity mix from CH mix to certified electricity mix (Step 2) and to install PV (Step 5). Regarding GHG emission mitigation substituting oil for wood is most cost-effective (Step 1) yielding a large mitigation effect.

To conclude, two measures namely using wood instead of oil and using low-carbon electricity mitigate GHG emissions effectively. Subsequent measures yield relatively high marginal GHG mitigation costs and are rather useful to increase PE efficiency.

The strategy reaches the SIA 2040 guide value for GHG emissions (6 $kgCO_{2eq}/m^2a$ for operation). In terms of PE only the guide value for operation and construction is reached (530 MJ/m^2a for operation). See Figure 27 and Figure 28.

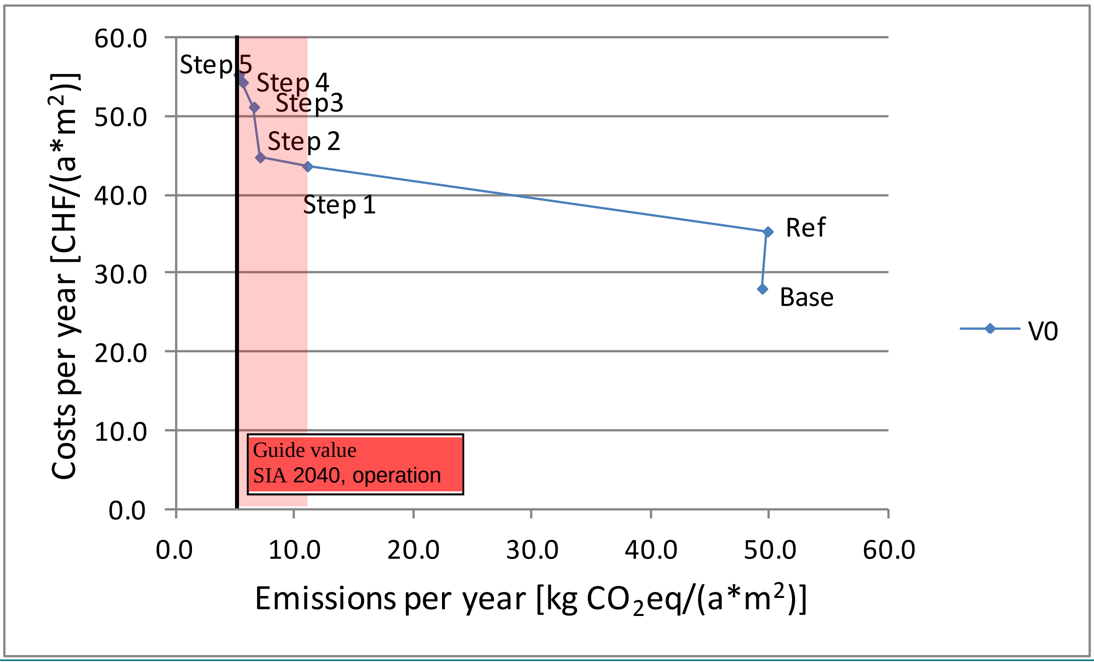

Figure 27: Yearly costs as a function of GHG emissions due to the strategy steps of the “GHG oriented” strategy compared to guide value “operation” and “operation+construction” of SIA 2040.

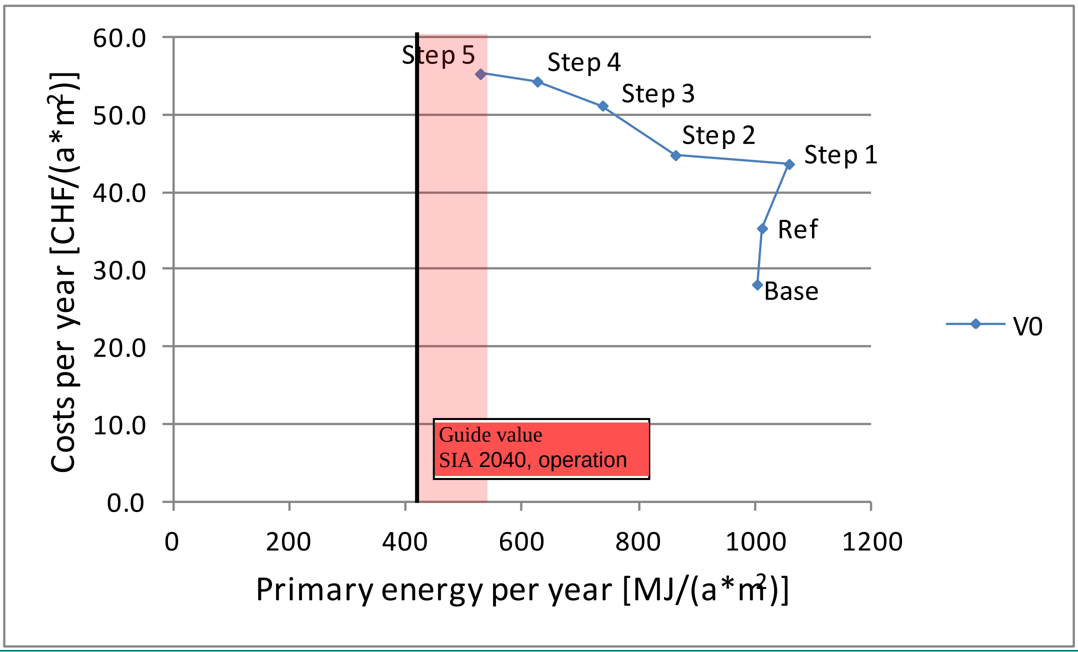

Figure 28: Yearly costs as a function PE efficiency increase due to the strategy steps of the “GHG oriented” strategy compared to guide value “operation” and “operation+construction” of SIA 2040.

In Figure 29 illustrates the yearly costs through the main strategy. The costs consist of three parts: energy, capital and operating plus maintenance costs. The share of the energy costs is decreased through the strategy. However, the share of the capital costs is increased.

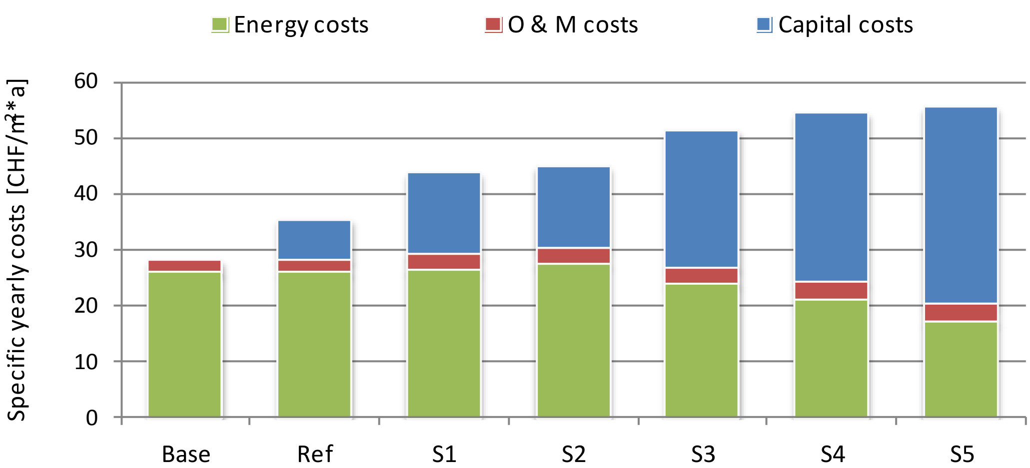

Figure 29: Specific yearly costs development depending on the steps of the strategy

The strategy variants of the “GHG oriented” strategy

Three different strategy variants are investigated (see Table 19). The most significant variant from the main strategy is within the first step in which the oil heating system is changed to an air heat pump, geothermal heat pump or to heat supply by a district heating system instead of a wood heating system. Each variant includes the same second, fourth and fifth step. The third step is divided into two levels where the higher insulation level is selected in the strategy variant V4 due to the lowest expected GHG emissions reduction.

		Different variants of the strat-egy			
		V0	V1	V2	V3
Step 1.V1	Wood pellets heating system	X			
Step 1.V2	Heat pump air		X		
Step 1.V3	Heat pump geothermal			X	
Step 1.V4	District heating Zürich mix 63% waste, 15% wood, 10% gas, 8% oil, 4% geo HP				X
Step 2	Certified electricity mix (ESU) 97.78% water, 0.83% wind, 0.73% biomass, 0.66% photovoltaic	X	X	X	X
Step 3a	Minergie-P **Windows:** Wood Standard, G-value 0.55, U-value 0.78	X	X	X	
Step 3b	Minergie-P **Façade:** Rockwool, Thickness 19 cm, U-value 0.15 **Windows**: Wood Standard, G-value 0.55, U-value 0.78				X
Step 4	Building automation level C to A, thermal energy	X	X	X	X
Step 5	PV P_p = 20 kW, 16000 kWh/a, 10% onsite use	X	X	X	X

Table 19: The steps of the main strategy and strategy variants.

The calculation results of the different strategy variants are shown in Figure 30 and Figure 31.

Below the results of different strategy variants, compared to the main strategy, allow for stating the following.

- The heat pump heating system in the strategy variants V1 and V2 reduces GHG emissions more effectively as compared to wood of the variant V0 but slightly less than the district heating system in the variant V3. This is due to the higher overall efficiency of the heat pumps but higher CO_2 content of electricity mix than district heating mix. However, the heat pump heating system is the most cost effective heating system in terms of GHG emissions. The total PE use is even increased with the heat pump heating system because of the used environmental heat of the heat pump and high PE intensity of the electricity mix. However, the heat pump is still more cost-effective than wood heating system. The GHG emissions reduction is the highest with the wood heating system in the main strategy compared to the other strategy variants. The wood heating system is the least cost-effective system in terms of PE reduction as it yields highest yearly costs and it even increases the PE use. The heat pump and district heating system result in significantly lower yearly costs and are quite good cost-effectiveness due to efficient energy use.

- In the second step electricity mix is changed from the CH-mix to the certified electricity mix. The change reduces the GHG emissions and PE factors. Hence, the second step has the highest impact on V2 and V3 because the energy carrier of the heat pump heating system is electricity. There is also GHG emissions and PE use reduction in V1 and V4 caused by the general electricity consumption of the building.
- The insulation and building automation measures (step 3 and step 4 respectively) decrease heating demand and hence, have the highest impact on the main strategy V0 and the strategy variant V3 in terms of GHG emissions and PE reduction. In these strategies the GHG emissions factors of the heating energy carriers are higher than in the strategy variants V2 and V3 (where these factors are low due to changed electricity mix). In the strategy variants V2 and V3 GHG emissions are even increased by the advanced insulation measures due to higher embodied energy and emissions. Moreover, the PE factors in V0 and V3 are lower but the heating system efficiencies are also lower and therefore, PE reduction is more significant if the heating demand is reduced. The yearly costs are increased in each strategy variant.

As a conclusion the other heating systems (heat pumps and district heating) reduce more cost effectively both GHG emissions and PE use than the wood heating system. The measures, that reduce heating demand, have the highest impact on PE use if the primary energy factor is relatively high and overall efficiency low. Thus, the variants with a heating system, which uses the certified electricity mix or low carbon intension district heat, reduces GHG emissions so effectively that the rest of the measures which do not have a significant reduction effect, but have high marginal costs.

The guide values of SIA 2040 for operation (6 $kgCO_{2eq}/m^2a$ and 450 MJ/m^2a) are reached in variants from V0 to V2 in terms of GHG emissions. In terms of PE use the variants from V1 to V3 because of the change of the heating system to the district heating or heat pump. See Figure 30 and Figure 31.

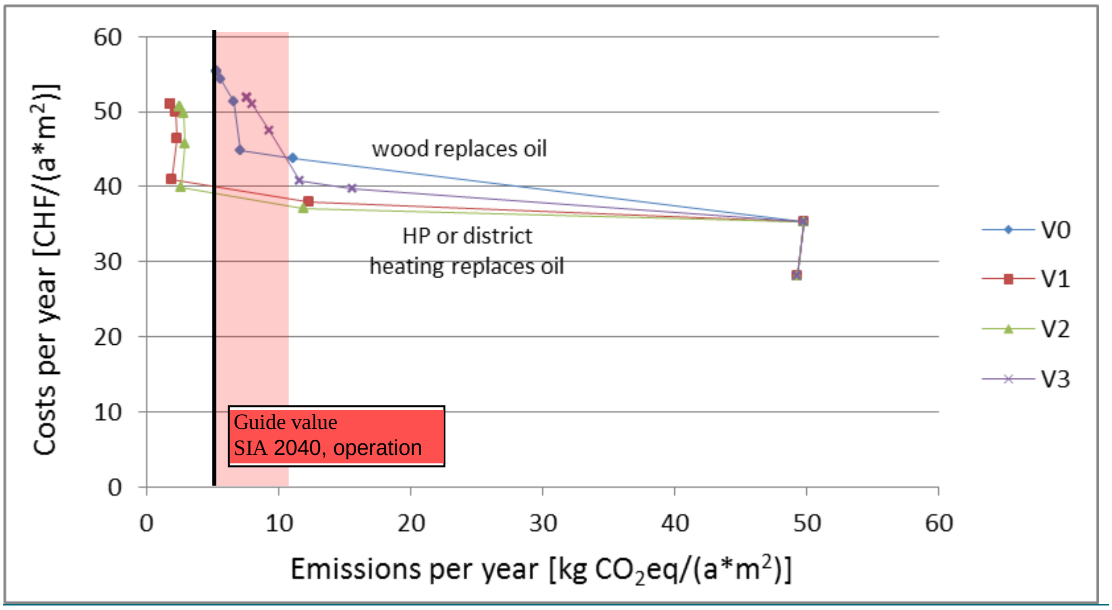

Figure 30: Yearly costs as a function of GHG emissions due to the strategy steps of the each strategy variant compared to guide value “operation” and “operation+construction” of SIA 2040.

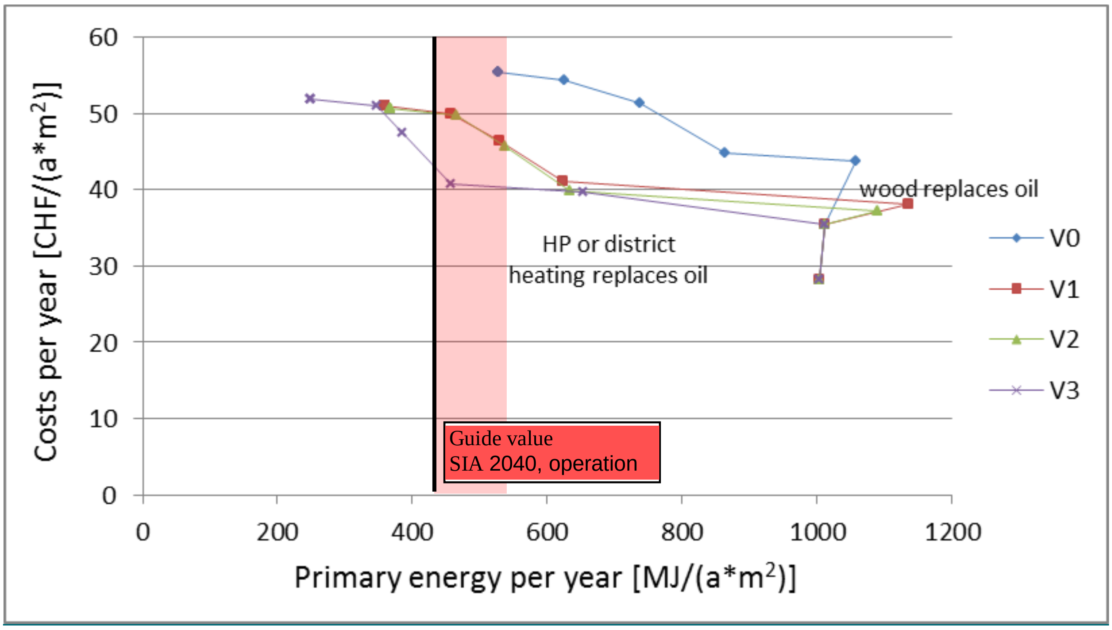

Figure 31: Yearly costs as a function of PE use due to the strategy steps of the each strategy variant compared to guide value “operation” and “operation+construction” of SIA 2040.

3.4.3 II.c. Rather rational, considering cost-effectiveness, resource (PE) oriented

The resource oriented “green” person is aware that increasing energy-efficiency of the building envelope is the foundation of effective environmental acting and that improving envelope insulation may reduce the energy demand for heating in the buildings by approximately half while also reducing GHG emissions by a similar amount as well as allowing for savings of investment costs due to energy systems with a lower load (power). He is also aware that measures requiring higher investment costs might be paid off during their life span. Moreover it is assumed that the resource oriented strategy is founded on a more holistic approach than the GHG oriented strategy, including also aspects such as co-benefits, typically being part of labels such as Minergie.

- Step 1 The first step of the resource oriented environmental strategy consists in decreasing the heating demand through envelope insulation (M1)
- Step 2 In addition to the envelope insulation a ventilation system with heat recovery is implemented to further reduce heating energy demand (M3). This approach is consistent with the principles of “Minergie”, "Minergie-P" and "Passive House" (within this framework a ventilation system is required).
- Step 3 The heating system is replaced by a new one with an appropriate energy carrier, but only to the extent necessary to meet the requirements of Minergie (M2). Regarding the choice of the heating system both GHG emissions and PE are considered from a LCA perspective. Instead of including certified energy products a systemic approach is chosen (e.g. average or marginal impacts). For instance, if available the district heating system is the preferred choice for remaining energy supply. This allows for the connection to an already established grid with low additional primary energy use related to the distribution system (if DH is based on waste combustion).
- Step 4 Embodied energy content is an additional evaluation criteria choosing among different options (as for example to insulate the building envelope, to install a ventilation or a heating system, M8)
- Step 5 As current electricity production is considered quite PE intensive using appliances with above-average energy-efficiency are chosen (M4)
- Step 6 Also, regulation and control measures are adopted in order to further decrease direct energy demand (electricity and heat).
- Step 7 Finally, to cover the remaining (low-level) energy demand implementing solar thermal panels and PV is an integral step of this resource-oriented strategy, since the energy consumption (or a major part of it) would be covered by renewable energy sources (M9).

The “resource oriented” strategy is divided into five different variants. The main strategy V0 and variants are described more detailed in Table 20. The main differences between the variants are in envelope insulation measures and heating systems. Each variant includes the same second, fourth, sixth and seventh step. Subsequently the results of the main strategy are presented first, followed by the results of the different strategy variants similarly to the previous strategies.

The results of the “PE oriented” main strategy

The results regarding GHG emissions mitigation and PE efficiency increase are represented in Figure 13 and 14, respectively.

The main function of the “resource oriented” strategy is to seek ambitious environmental goals even if not all measures are economically viable. The resource oriented person concentrates to reduce primary energy use:

Step 1 A comprehensive Minergie labelled ventilated façade insulation is undertaken. This measure reduces space heating demand and thus, GHG emissions and PE use. Additionally, the yearly costs are staying almost constant due to energy savings (see Figure 34).

Step 2 The ventilation system with heat recovery reduces GHG emissions and PE use due to reduced space heating demand and the relatively high CO_2 content and PE factor of the heating energy carrier (oil). However, the yearly costs are increased significantly due to the fact that investment costs are not paid off by energy savings and due to additional operation costs.

Step 3 Replacing the oil heating system by a district heating system results in both significant reductions of GHG emissions and PE use. The yearly costs are increased only slightly due to energy cost savings.

Step 4 Embodied energy content of renovation measures is an additional evaluation criteria choosing among different options. Due to this the construction design and material choice of the façade insulation are changed to have lower embodied energy and GHG emissions. Instead of the ventilated glass wool façade insulation a compact EPS insulation is selected still complying with the Minergie label. This step slightly decreases GHG emissions and PE use due to reduced embodied energy and GHG emissions but the effect is almost not visible. However, it increases the yearly costs slightly due to the 10 years shorter expected lifetime of the compact façade.

Step 5 The old appliances are replaced by above-average energy-efficient ones. This change reduces electricity consumption and thus, GHG emissions and PE use. The reduction has a high impact on PE use due to the high PE factor of the used CH electricity mix. The impact on GHG emissions is limited because of the low GHG emissions factor. Additionally, the replacement reduces slightly the yearly costs.

Step 6 The building automation level is enhanced from the level C to A. This enhancement decreases space heating, hot water and electricity consumption. Due to this GHG emissions and PE use decrease. The impact on PE use is slightly more significant due to the high PE factor of the used CH electricity mix. However, the yearly costs increase significantly due to the upfront investment and low energy cost savings.

Step 7 The PV installation decreases both GHG emissions and PE use due to the on-site use. The own electricity generation decreases the amount of purchased CH electricity mix which has a relatively high PE factor and CO_2 content. Additionally, the installation increases only slightly the yearly costs due to the investment costs that are almost compensated by the savings from the on-site use and sale of electricity.

As a conclusion the façade insulation measure and the ventilation system with heat recovery decrease both GHG emissions and PE use effectively since the used heating energy carrier is quite carbon and PE intensive. Additionally, the choice of low embodied energy construction design and materials has a slight impact on PE use and GHG emissions. The district heating system reduces significantly GHG emissions and PE use compared to the oil heating system. The measures, that reduce electricity consumption, have a high impact on GHG emissions and PE use if the used electricity mix has relatively high GHG emissions and PE energy factors. The steps 1 (façade insulation), 3 (district heating), 5 (more efficient appliances) and 7 (PV) are the most cost effective steps due to the least steep increase in the yearly costs. The other steps are not cost effective.

In terms of PE the strategy reaches the guide value for operation (530 MJ/m^{2}a). In terms of GHG emissions the SIA 2040 guide value for operation (6 kgCO_{2eq}/m^{2}a) is not reached. However, the guide value for operation and construction (11 kgCO_{2eq}/m^{2}a) is reached. See Figure 32 and Figure 33.

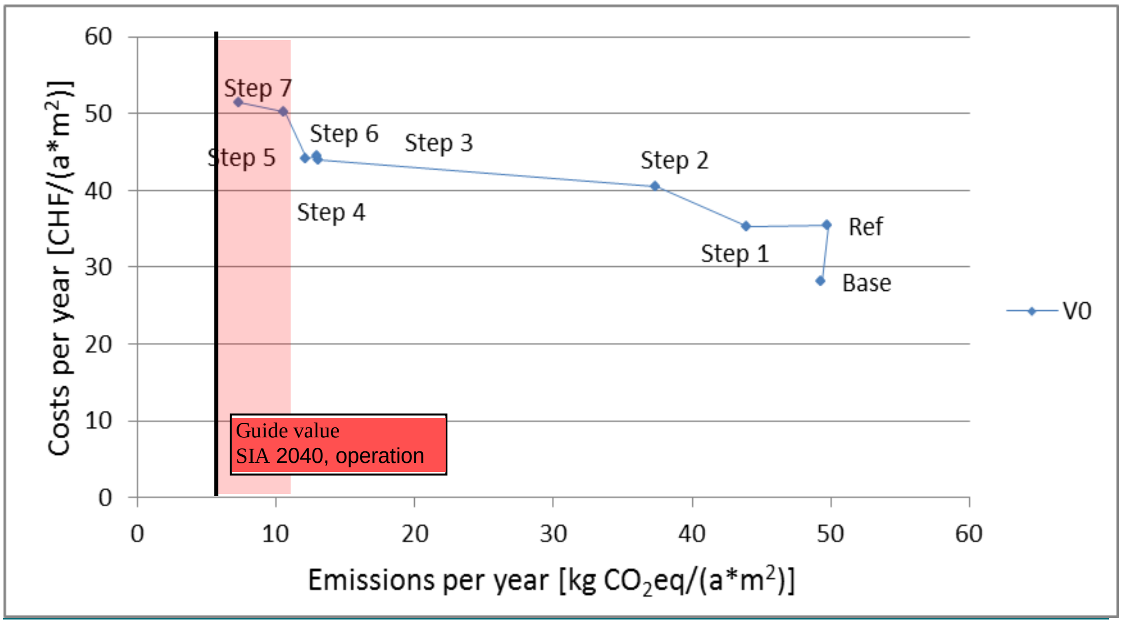

Figure 32: Yearly costs as a function of GHG emissions due to the strategy steps of the "PE oriented" strategy compared to guide value "operation" and "operation+construction" of SIA 2040.

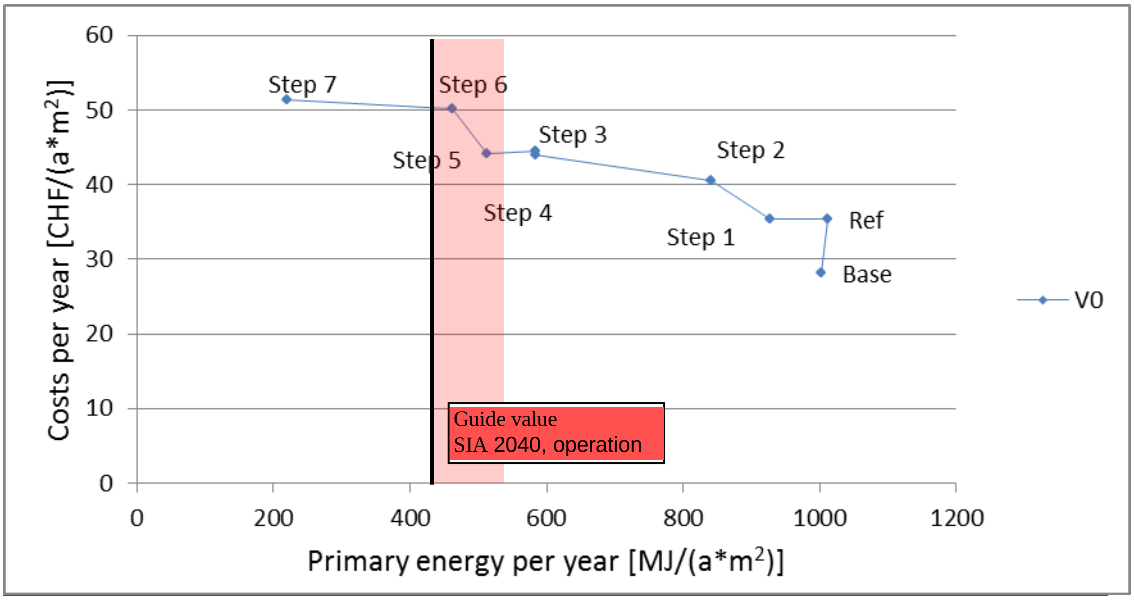

Figure 33: Yearly costs as a function PE efficiency increase due to the strategy steps of the "PE oriented" strategy compared to guide value "operation" and "operation+construction" of SIA 2040.

In Figure 34 the yearly costs through the main strategy are represented. The costs consist of three parts: energy, capital and operation plus maintenance costs. The share of the energy costs decreases more or less evenly from step 1 to step 7. However, the share of the capital costs increases, especially in the case of steps 2, 6 and 7.

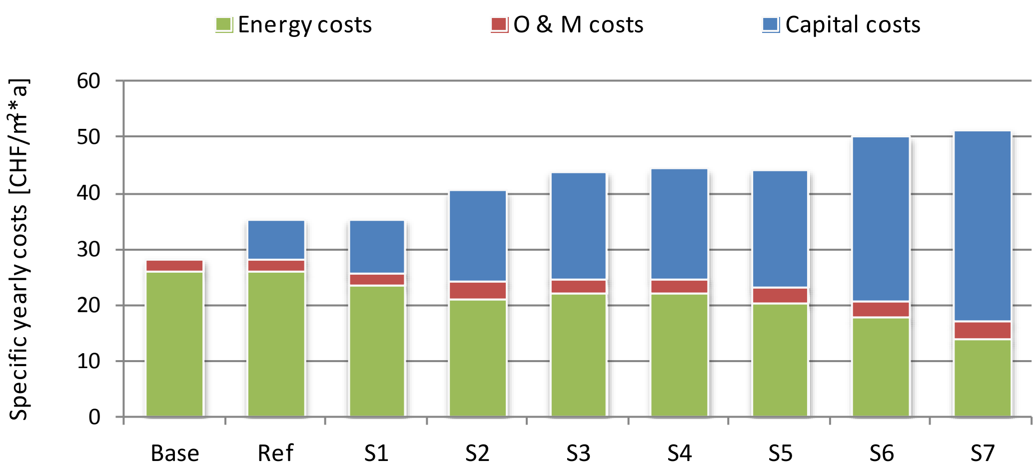

Figure 34: Specific yearly costs development depending on the steps of the "PE oriented" strategy

The strategy variants of the "PE oriented" strategy

Five different strategy variants are investigated. The most significant variant from the main strategy is within the first step in which different envelope insulation measure are undertaken. Each variant includes the same second, third, fourth, sixth and seventh step.

The fifth step is divided into two levels where either appliances or appliances and lighting are affected by energetic renewal.

		Different variants of the strategy					
		V0	V1	V2	V3	V4	V5
Step 1a	Minergie **Façade:** Glass wool, Thickness 12 cm, U-value 0.20	X					
Step 1b	Minergie **Façade:** Glass wool, Thickness 12 cm, U-value 0.20 **Windows**: Metal, G-value 0.55, U-value 0.95		X				
Step 1c	Minergie **Façade:** Glass wool, Thickness 12 cm, U-value 0.20 **Roof:** Glass wool, Thickness 13 cm, U-value 0.20 **Windows:** Metal, G-value 0.55, U-value 0.95			X			
Step 1d	Minergie-P **Façade:** Glass wool, Thickness 19 cm, U-value 0.15				X		
Step 1e	Minergie-P **Façade:** Glass wool, Thickness 19 cm, U-value 0.15 **Windows**: Metal, G-value 0.45, U-value 0.80					X	
Step 1f	Minergie-P **Façade:** Glass wool, Thickness 19 cm, U-value 0.15 **Roof:** Glass wool, Thickness 20 cm, U-value 0.15 **Windows:** Metal, G-value 0.45, U-value 0.80						X
Step 2	Ventilation system with heat recovery η_{el} = 0.6 η_{WRG} = 0.80 ventilated area 75%	X	X	X	X	X	X
Step 3	District heating Zürich mix 63% waste, 15% wood, 10% gas, 8% oil, 4% geo HP	X	X	X	X	X	X
Step 4	Low embodied PE and GHG emissions in insulation materials and efficiency label reduction in V3 to V5	X	X	X	X	X	X
Step 5a	Above average efficient electricity services, appliances	X	X	X			
Step 5b	Above average efficient electricity services, appliances and lighting				X	X	X
Step 6	Building automation from C to A	X	X	X	X	X	X
Step 7	PV P_p = 20 kW, 16000 kWh/a, 20% onsite use	X	X	X	X	X	X

Table 20: The steps of the main strategy and strategy variants.

The calculation results of the different strategy variants are shown in Figure 35 and Figure 36, and the numeric values are indicated in Table? in the Annex.

Subsequently, the results of different strategy variants, compared to the main strategy, are discussed.

- During the first step different envelope measures are undertaken. The highest GHG emissions and PE reduction is reached by the most comprehensive envelope insulation in the strategy variants V2 and V5 due to the high reduction of the space heating demand. However, this insulation leads also to the highest life cycle costs due to the high upfront investment of the windows. The combination of insulation measures on the façade and window replacement in V1 and V4 yield a higher reduction of GHG emissions and PE use than the comprehensive façade insulation in the main strategy V0 and variant V3. The base and reference cases already include energetic renewal of the basement. The costs depend on the number of the building elements affected by energetic renovation. The Minergie-P and Minergie labeled insulation measures result in almost the same life cycle costs even if insulation measures for Minergie-P are more expensive. This occurs because of the lower heating demand in the case of Minergie-P.
- A ventilation system with heat recovery (step 2) decreases GHG emissions and primary energy use in each variant. The influence of the system with heat recovery is independent on the other measures. The extent of the ventilation system influence depends on GHG emissions and PE factors of the heating energy carrier.
- The oil heating system is replaced by a district heating system. A wood heating system is not selected because the strategy seeks primary energy reduction and co-benefits of the measures and wood heating increases primary energy demand due to the lower heating system efficiency than oil heating. Despite of a high overall efficiency a heat pump heating system is not selected due to environmental impact which increases PE use. The district heating system decreases significantly GHG emissions and PE use due to low CO_2 content and PE factor. Additionally, the LCC are only slightly increased due to a balance between the upfront investment and savings of energy cost.
- Choice of construction design and materials of the envelope insulation measures in the first step are changed to have lower embodied primary energy use and GHG emissions. Additionally, in the variants V3 to V5 the energy efficiency label is reduced in order to see a net effect. The new features are described in Table 21. These decrease the insulation level of the building envelope, especially the change from Minergie-P to Minergie in the variants V3 to V5, but they also reduce embodied energy and GHG emissions. Therefore, this may lead to higher heating demand which reduces the benefit of lower embodied energy. In the strategy variants V1 and V2 the GHG emissions are reduced slightly when the construction design and material are changed but the Minergie label is fulfilled. In the variant V1 PE use is increased slightly due to increased window frame share. In the strategy variants V3 and V4 GHG emissions are reduced but PE use is slightly increased due to having compliance with the requirements of the Minergie label.

In the variant V5 a comprehensive insulation measure is undertaken which reduces both GHG emissions and PE use even if only the Minergie instead of the Minergie-P label is achieved. (Lower insulation level and higher U-values).

- If the efficiency level of both appliances and lighting is enhanced (V3 to V5), slightly higher GHG emissions and PE reduction is reached. As compared to appliances only. Additionally, the costs are reduced due to savings of energy costs which are higher than upfront investment costs.

Feature	Façade	Roof	Window
Measure	From a ventilated façade to a compound façade	From a new construction to a new construction with inside insulation	Window replacement
Insulation level	Minergie, 11 cm	Minergie, 13 cm	Minergie
Material	EPS	Rock wool	Frame material from metal to wood
U-value	0.20 W/m^2K	0.20 W/m^2K	0.95 W/m^2K

Table 21: The new features of the insulation measures.

As a conclusion the insulation level of the building envelope influences to the amount of the GHG emissions and PE reductions. However, better insulation level increases also the life cycle costs. The benefit of low embodied energy insulation measures increases if the number of building elements affected by energy-efficient renovations increases. The most cost effective step is to have a high efficiency level of both appliances and lighting. Thus, the yearly costs decrease. Additionally, the façade insulation, district heating system and PV installation are cost effective measures compared to the other steps due to an almost flat slope of the costs increase. In the case of the other steps the yearly costs increase.

The all variants of the “PE oriented” strategy reach the PE guide value 450 MJ/m^2a for operation. However, any strategy variants do not reach the SIA 2040 guide value of the GHG emissions (6 $kgCO_{2eq}/m^2a$) but some of them gets really close. See Figure 35 and Figure 36.

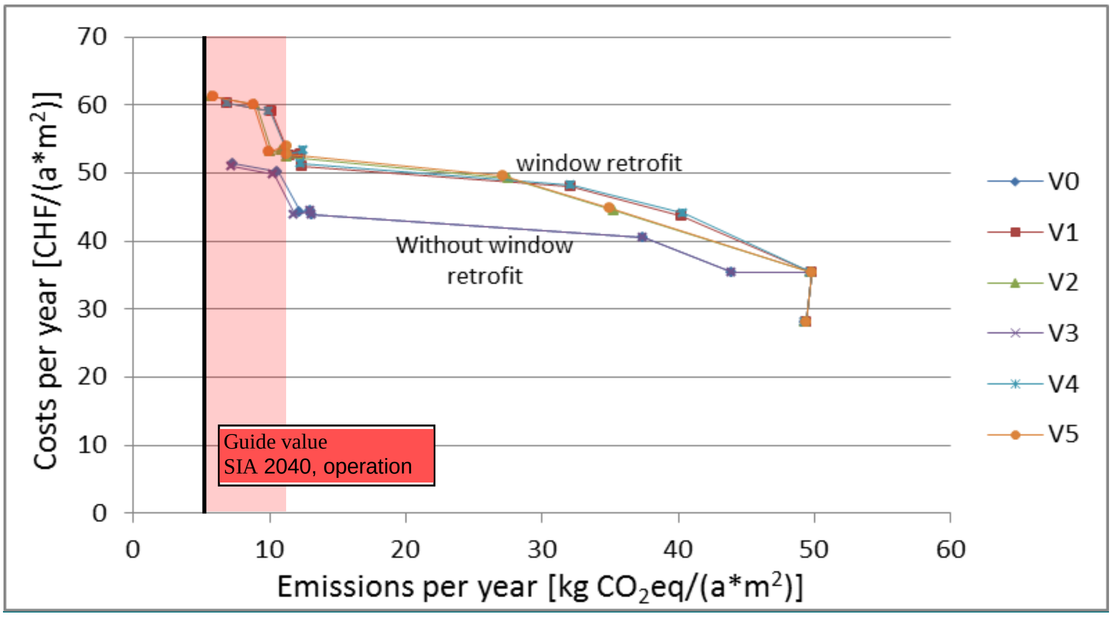

Figure 35: Yearly costs as a function of GHG emissions due to the strategy steps of the each strategy variant compared to guide value “operation” and “operation+construction” of SIA 2040.

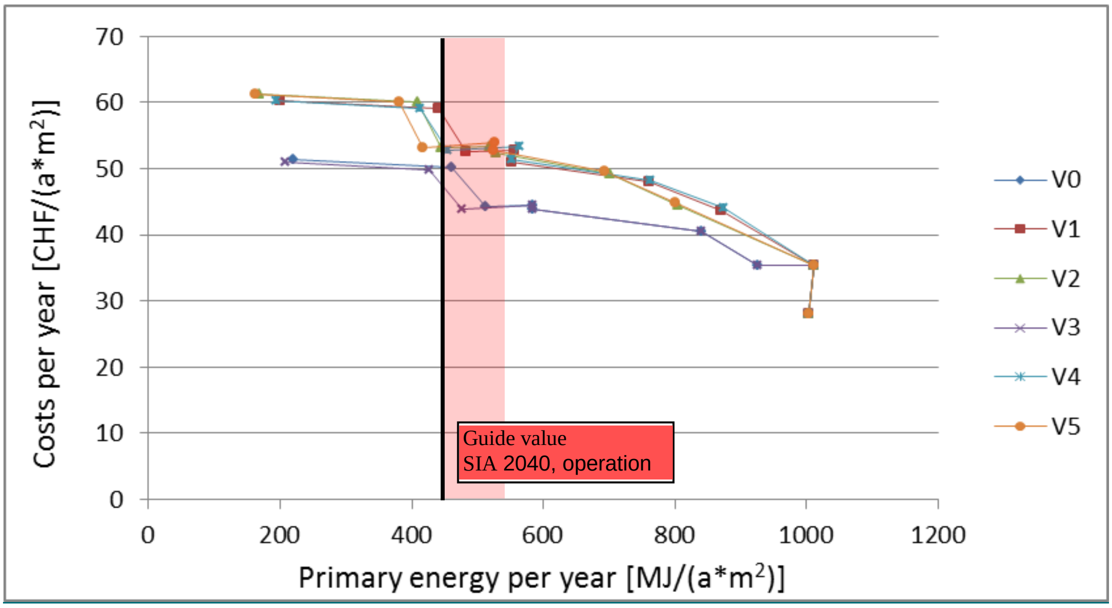

Figure 36: Yearly costs as a function of PE use due to the strategy steps of the each strategy variant compared to guide value “operation” and “operation+construction” of SIA 2040.

3.5 III. “Technology focus”

The technology oriented personality rather believes in merits and potentials of advanced technologies. As such optimal results can primarily be achieved by technology improvements. Construction type measures, such as façade insulation or roof remodelling appear too cumbersome and too costly, also in terms of investment costs, to his vision.

Step 1 The technology strategy starts with the lowest level of interaction within the residential space and specifically with a change of the controls of the energy-related building systems and applications (M6).

Step 2 The implementation of more efficient electricity based energy services such as more efficient appliances is also seen as easily achievable goal, since it does not require any construction work or labour (M4).

Step 3 When replacing the heating system, heat pumps or co-generation systems are part of the possible choice set (M2).

Step 4 A ventilation system with heat recovery is also a typical part of the technology related energy improvements. This measure decreases the heat losses compared to natural or simple mechanical ventilation (M3).

Step 5 The final step of this strategy is the implementation of solar thermal and/or PV systems (M7).

In addition to the "technology focus" strategy a one strategy variant is studied. The main strategy V0 and variant V1 are described more detailed in Table 22. The main differences between the main strategy and variant V1 are on the level of the technology enhancement and selected heating system. The main strategy has selections of lower technology enhancement but a higher efficiency heating system. The strategy variant has selections other way around. Subsequently the results of the main strategy are presented first, followed by the results of the different strategy variants similar to the previous strategies.

The results of the "technology focus" main strategy

The results regarding GHG emissions mitigation and PE efficiency increase are represented in Figure 37 and Figure 38, respectively.

The main function of the "technology focused" strategy is to seek technology improvements and to avoid construction type measures:

Step 1 The enhancement of the building automation level from C to B decreases space heating, hot water and electricity demand. Due to this GHG emissions and PE use are reduced. However, the life cycle costs are increased slightly due to the upfront investment costs not completely paid off by savings of energy costs. The reduction of GHG emissions and PE use is relatively high due to the high GHG emissions and PE factors of oil. Additionally, the used CH electricity mix has a quite high PE factor.

Step 2 The improved energy efficiency of appliances causes only a minor reduction of GHG emissions due to the low GHG emissions factor of CH electricity mix. The impact of efficiency improvement on PE use is relatively high due to the high PE factor of the CH electricity mix. The yearly costs increase slightly.

Step 3 Replacing the oil heating system by an air heat pump decreases significantly GHG emissions because the CO_2 content of the heating energy carrier is reduced and heating system efficiency increases significantly. The total PE use is increased because of the used environmental heat and high PE intensity of the used electricity mix. The yearly costs increase only slightly due to the balance between the upfront investment costs and energy cost savings caused by the replacement. A seasonal COP of the heat pump was assumed and electricity is significantly more expensive than oil.

Step 4 The ventilation system with heat recovery reduces both GHG emissions and PE use. However, the impact of the change of heating energy carrier on PE use is higher than the impact of the ventilation system. The yearly costs increase significantly due to the fact that the investment costs are not paid off by energy cost savings and due to additional operational costs for the maintenance and electricity consumption of ventilation.

Step 5 On-site PV installation decreases both GHG emissions and PE use. Electricity generation decreases the amount of purchased CH electricity mix which has a relatively high PE factor and CO_2 content. Additionally, the installation increases only slightly the yearly costs due to the investment costs that are almost compensated by the savings from the on-site use and sale of electricity.

As a conclusion due to the CH electricity mix used, the impact of changing the heating system reduces predominantly GHG emissions. The impact on PE reduction is less significant because of the high PE factor of the used electricity mix. The amount of the GHG emissions and PE reductions due to the measures reducing heating or electricity demand depends on the magnitude of the energy carriers' GHG emissions and PE factors. Due to the almost constant yearly costs, the most cost effective measure is to change the heating system (step 3) and to install PV (step 5). All the other steps are not cost effective due to the increased yearly costs.

The strategy reaches nor the guide value for operation (450 MJ/m^2a) in terms of PE neither in terms of GHG emissions (6 $kgCO_{2eq}/m^2a$). However, the guide value for the combination of operation in terms of GHG emission is reached. See Figure 37 and Figure 38.

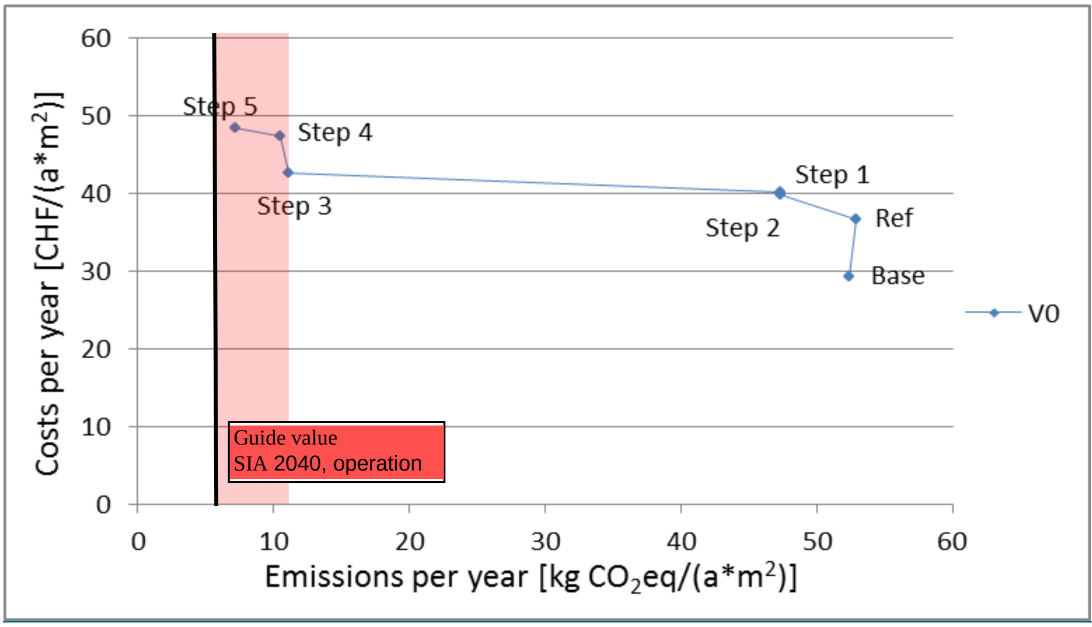

Figure 37: Yearly costs as a function of GHG emissions due to the strategy steps of the "technology focus" strategy compared to guide value "operation" and "operation+construction" of SIA 2040.

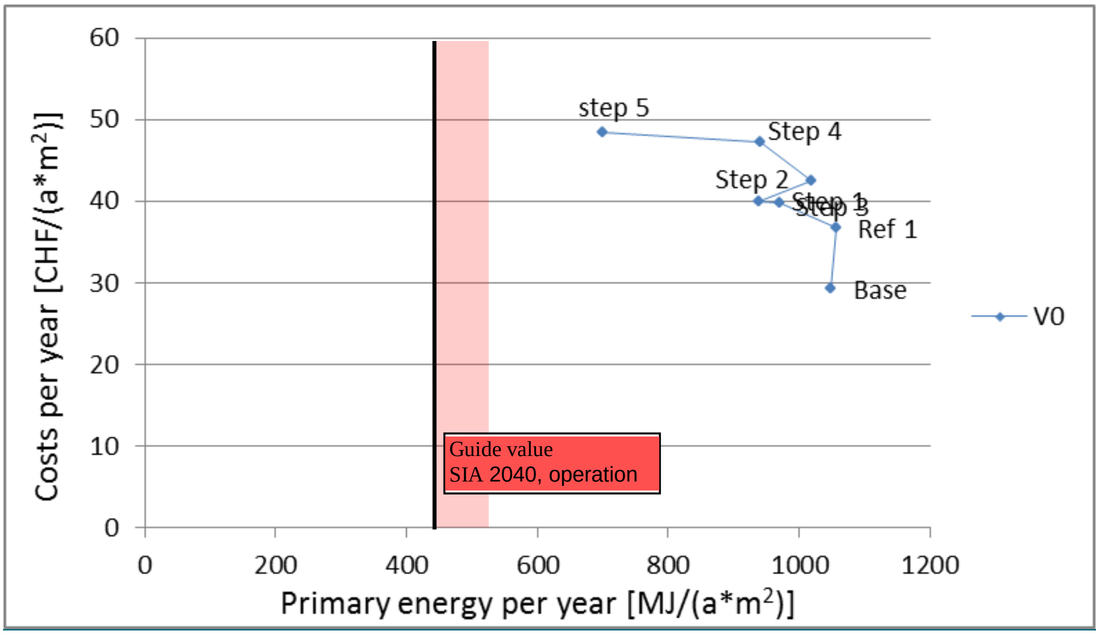

Figure 38: Yearly costs as a function PE efficiency increase due to the strategy steps of the "technology focus" strategy compared to guide value "operation" and "operation+construction" of SIA 2040.

In Figure 39 the life cycle costs of the main strategy are represented. The costs consist of three parts: energy, capital and maintenance plus operating costs. The share of the energy costs decreases quite evenly from step 1 to step 5. However, the share of the capital costs is increases, especially in steps S4 (ventilation system) and S5 (PV installation).

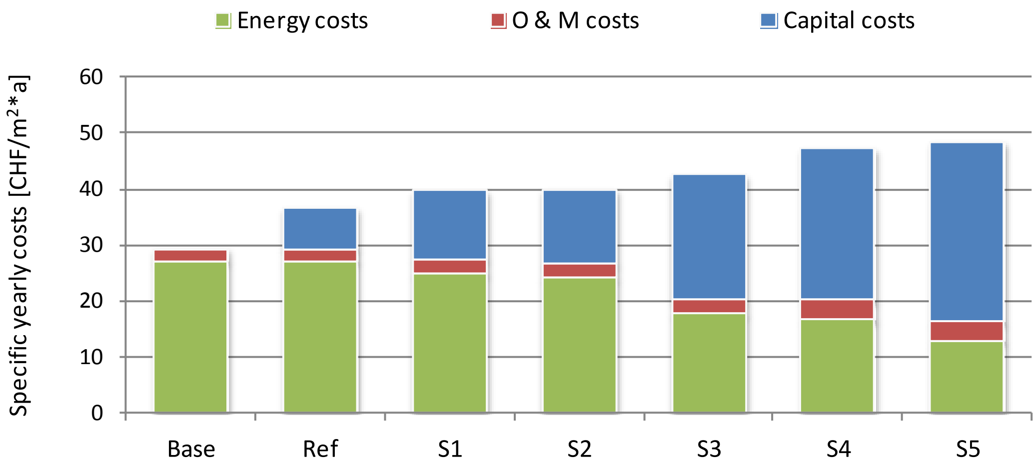

Figure 39: Specific yearly cost development depending on the steps of the strategy.

The strategy variants of the "technology focused" strategy

Besides the main strategy V0 only one strategy variant V1 is investigated. In the variant V1 the measures of the first, second and fourth steps have higher energy efficiency than in the main strategy (for example building automation and appliances efficiency level). Hence, a heat pump with lower energy efficiency is selected in the strategy variant V1. The fifth step in the main strategy and in variant V1 is the same.

		Different variants of the strategy	
		V0	V1
Step 1a	Building automation from C to B	X	
Step 1b	Building automation from C to A		X
Step 2a	Average efficiency of electricity services, appli-ances	X	
Step 2b	Above average efficiency of electricity services, appliances		X
Step 3.V0	Heat pump geothermal	X	
Step 3.V1	Heat pump air		X
Step 4a	Ventilation system with heat recovery η_{el} = 0.4 η_{WRG} = 0.65 Ventilated area 75%	X	
Step 4b	Ventilation system with heat recovery η_{el} = 0.6 η_{WRG} = 0.90 Ventilated area 75%		X
Step 5	PV P_p = 20 kW, 16'000 kWh/a, 20% onsite use	X	X

Table 22: The steps of the main strategy and strategy variants.

The results of the calculations for the different strategy variants represented in Figure 40 and Figure 41, and documented in Table? in the Annex allow for the following findings:.

- As compared to V0, the higher efficiency levels of the building automation (step 1b) and appliances (step 2b) in the strategy variant V1 reduce more effectively both GHG emissions and PE use. However, the yearly costs increase due to the upfront investment costs which are not paid off by energy cost savings in the case of building automation enhancement. In contrast the higher efficiency level of appliances (reducing cost savings of building automation measures) reduces the yearly costs due to relatively high energy cost savings.
- Due to the lower overall efficiency, the air heat pump (V1) reduces GHG emissions less than the geothermal heat pump. However, with more efficient building automation and appliances the total reduction is more than in the variant V0 with geothermal heat pump but the yearly costs are slightly higher. The total PE use is increased due to the used environmental heat and high PE intensity of the electricity mix. In the variant V1 the PE use increase is higher because of the lover COP of the air heat pump.

- The ventilation system with heat recovery (step 4) reduces more effectively GHG emissions and PE if an air heat pump is used because of the lower heating system efficiency of the latter. Due to the higher heat recovery rate the reductions are also higher than in the case of the main strategy V0.

As a conclusion the higher energy efficiency of the first, second and fourth measures result in better GHG emissions and PE reductions but also in higher costs. Finally, lower upfront investment in the energy efficiency measures (step 1 and 2) and higher investment in the heating system efficiency in the main strategy V0 leads to lower GHG emissions and PE reductions than in the variant V1. However, lower yearly costs are reached in V0. Within the technology focused strategy the second, third and fifth steps (appliances, heat pump and PV installation, respectively) are the most cost effective steps yielding the least steep increase of the costs.

A cross comparison between the two main environmental indicators considered highlights that GHG emissions are reduced more effectively than PE use, a finding which is particularly prominent in this technology focused strategy, but can also be observed in the case of other strategies. Interestingly cost-effectiveness is quite different across the different measures in the case of GHG emissions mitigation (illustrated by different “steepness” of the curves in Figure 40), but quite similar in the case of PE use (more or less same “steepness”, see Figure 41)

The SIA 2040 guide value for operation in terms of GHG emissions (6 $kgCO_{2eq}/m^2a$) is reached by V1. In terms of PE the guide value (450 MJ/m^2a) for operation is not reached. See Figure 40 and Figure 41.

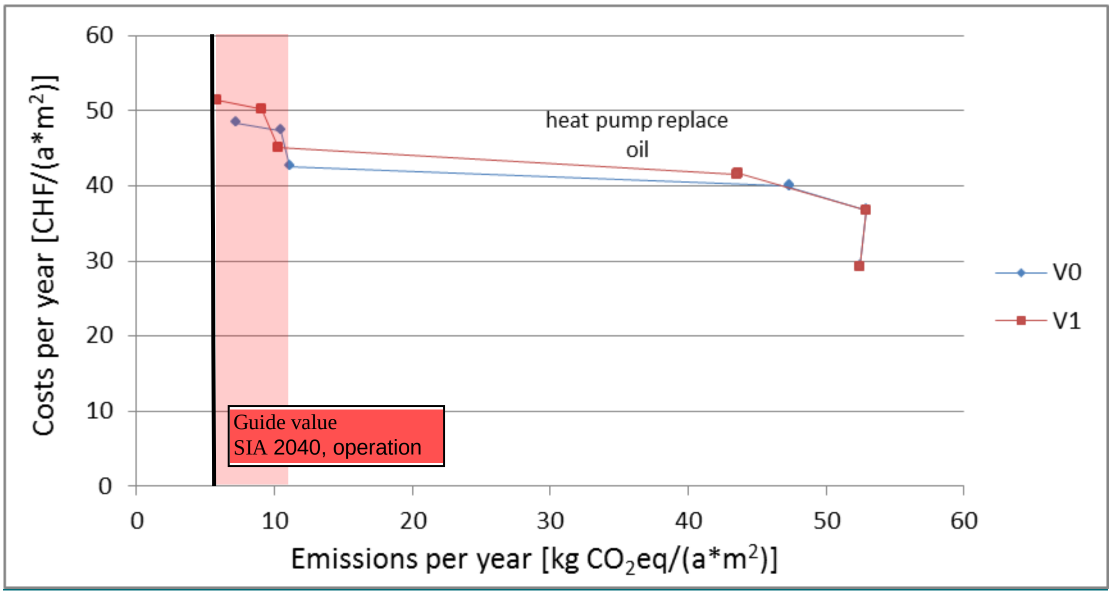

Figure 40: Yearly costs as a function of GHG emissions due to the strategy steps of the each strategy variant compared to guide value “operation” and “operation+construction” of SIA 2040.

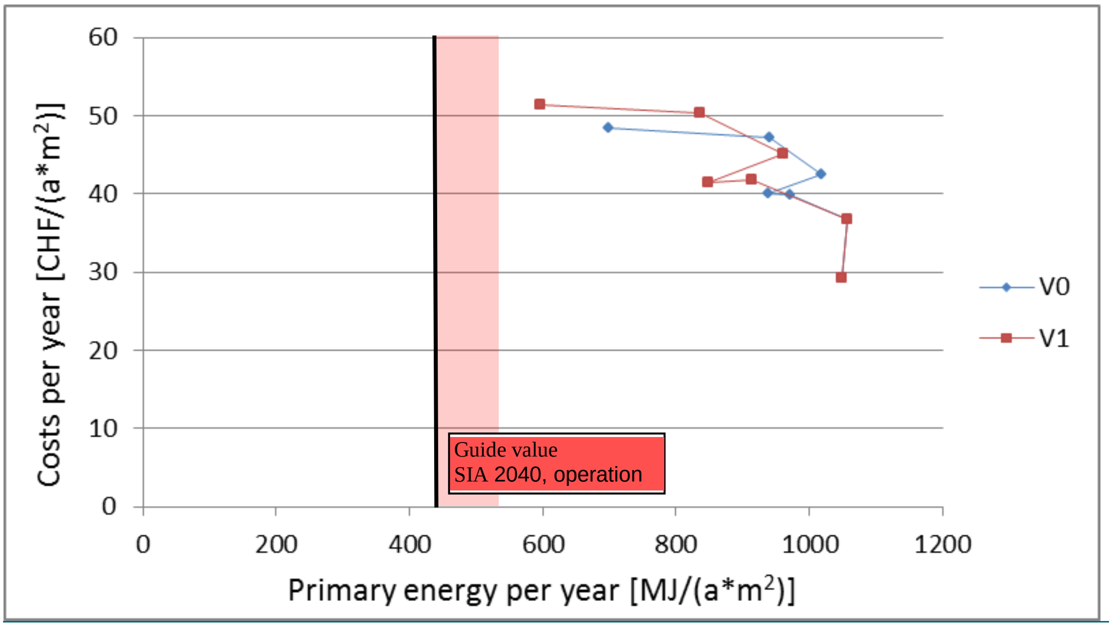

Figure 41: Yearly costs as a function of PE use due to the strategy steps of the each strategy variant compared to guide value “operation” and “operation+construction” of SIA 2040.

3.6 IV. “Life cycle cost optimizer”

As outlined above three different life cycle cost optimizing strategies are considered:

- IV.a: targeting GHG emissions reduction
- IV.b: targeting PE efficiency increase
- IV.c: targeting both PE and GHG

As opposed to the strategy types I to III cost-optimal strategies cannot be predefined fully prior to having calculated costs and benefits of individual measures. Thus, the strategy elements and their order will be specified after knowing the cost-benefit ratio of each of the measures.

3.6.1 IV.a: Targeting GHG emissions reduction

The “life cycle cost optimizer” strategy targeting GHG emissions reduction seeks ambitious environmental goals with the lowest costs. By using the results of the “GHG oriented” strategy the main strategy V0 includes only two steps in order to reduce GHG emissions with the optimal costs. In the strategy variant V1 additional steps are investigated. The main strategy and variant V1 are described more detailed in Table 23. Subsequently the results of the main strategy are presented first followed by the results of the different strategy variants, similar to the previous strategies.

The “life cycle cost and GHG optimizer” main strategy

The results regarding GHG emissions mitigation and PE efficiency increase are represented in Figure 42 and Figure 43, respectively.

The main function of the strategy is to reduce GHG emissions with optimal life cycle costs:

Step 1 The electricity supply mix is changed from the CH-mix to the certified electricity mix including hydropower, photovoltaic, wind and biomass (similar to the Zurich EWZ mix naturpower and ökopower product). The new electricity supply mix has a lower CO_2 content than the CH consumption mix (ESU Services, 2012). Due to this change the GHG emissions are mitigated. Additionally, the primary energy factor is lower than in CH-mix and thus, PE use is reduced as well. The yearly costs increase slightly because of the higher price of certified electricity (0.311 CHF/kWh vs. 0.277 CHF/kWh).

Step 2 Replacing the oil heating system by a geothermal heat pump reduces significantly GHG emissions due to the high heating system efficiency and certified electricity mix which has a low CO_2 content and a low PE factor. However, the PE use reduction is not that significant than the GHG emissions reduction due to the environmental heat used by the heat pump, which increases the total PE use. Additionally, the costs are increase more significantly than in terms of GHG emissions. The selection of the heating system is based on the results in the “GHG oriented” strategy. The yearly energy costs are decreased due to better heating system efficiency of the heat pump. However, energy savings are not enough to compensate the increased capital cost which results to increased yearly costs by 3 CHF/m^2a (see Figure 44).

As a conclusion the maximum possible GHG emissions reduction is almost reached by using a heat pump as a heating system and certified electricity for both the heat pump and general electricity use. Additionally, the final yearly costs increase only 4 CHF/m^2a compared to the reference case. All of the strategy steps carried out are almost cost effective, illustrated by a quite small increase of the costs.

The strategy reaches the guide value for operation (6 $kgCO_{2eq}/m^2a$ and 450 MJ/m^2a) only in terms GHG emissions. See Figure 42 and Figure 43.

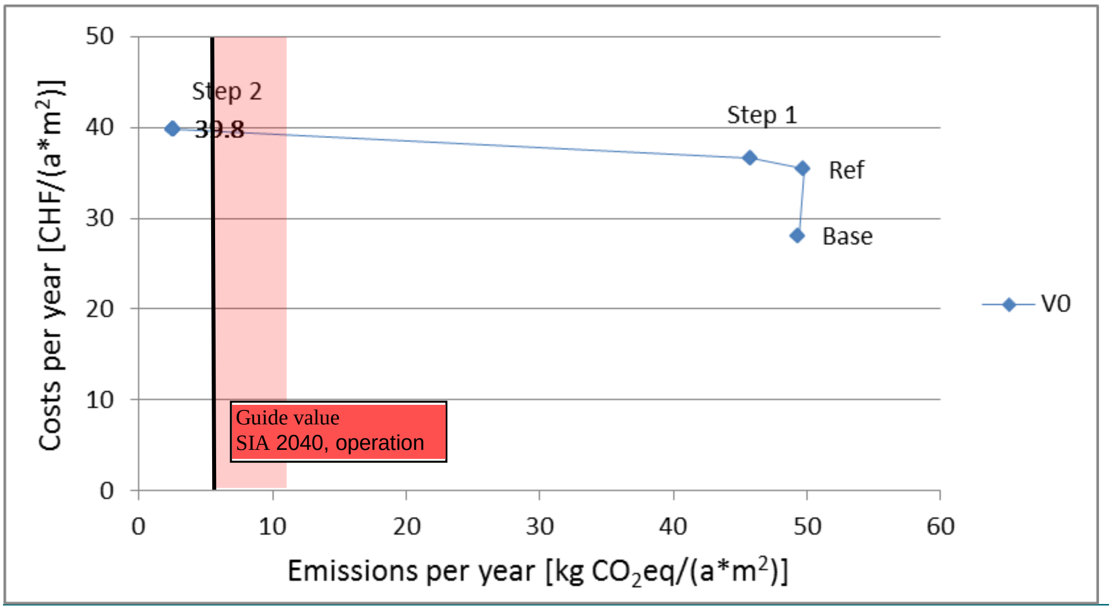

Figure 42: Yearly costs as a function of GHG emissions due to the strategy steps of the "LCC and GHG optimizer" strategy compared to guide value "operation" and "operation+construction" of SIA 2040.

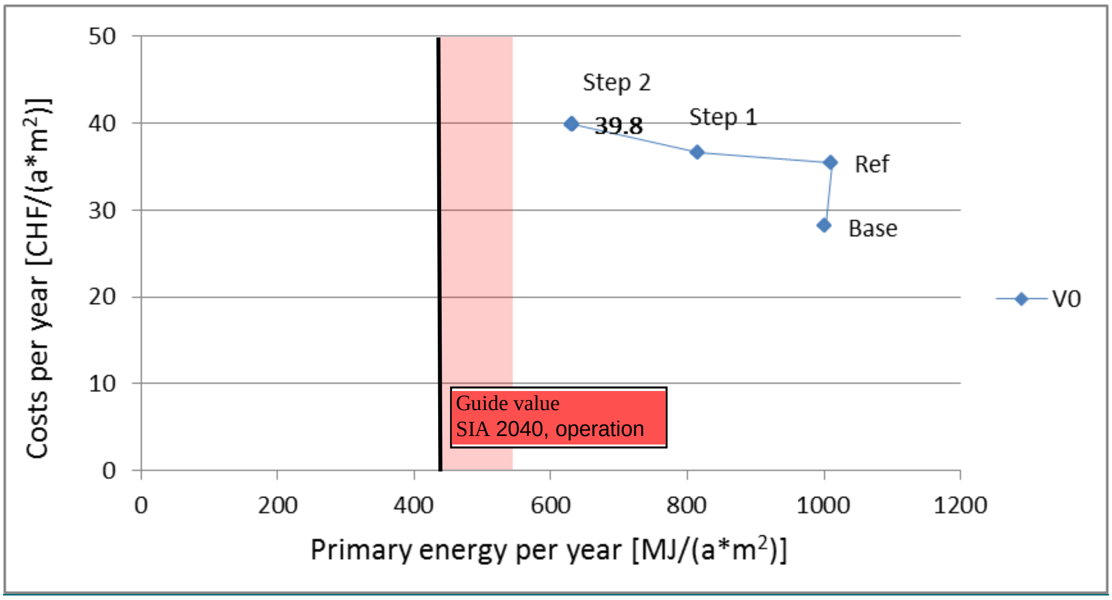

Figure 43: Yearly costs as a function PE efficiency increase due to the strategy steps of the "LCC and GHG optimizer" strategy compared to guide value "operation" and "operation+construction" of SIA 2040.

In Figure 44 the life cycle costs of the main strategy are represented. The costs consist of three parts: energy, capital and maintenance plus operating costs. The share of the energy costs decreases in the second step. However, the capital costs increase is higher than the reduction of energy costs in step 2.

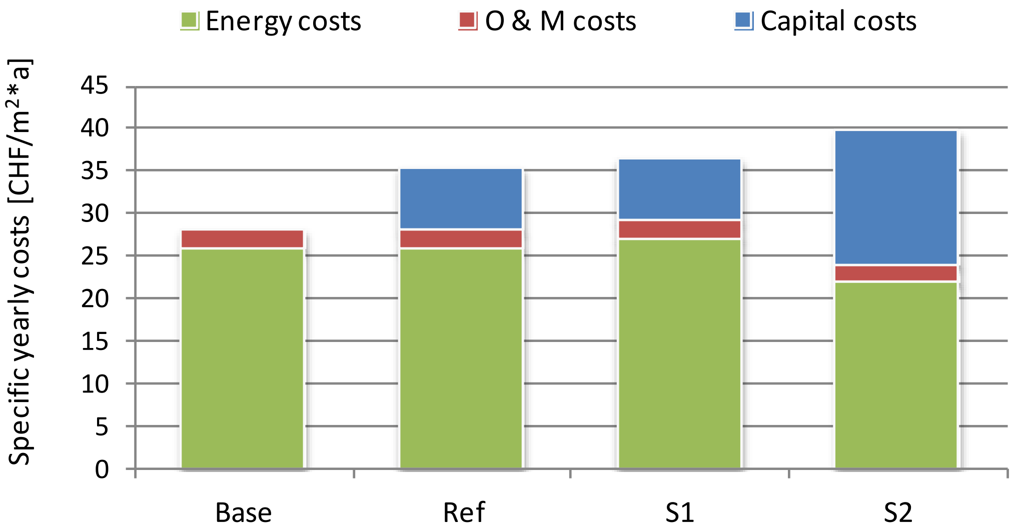

Figure 44: Specific yearly cost development depending on the *"life cycle cost and GHG optimizer"* strategy steps.

The strategy variants of the **"life cycle cost and GHG optimizer"** *strategy*

In addition to the main strategy V0 four additional strategy steps (step 3 – step 6) are assessed in strategy variant V1. These measures were expected to reduce GHG emissions when the strategies were defined before the calculations. Step 1 and step 2 are the same as in the main strategy.

		Different variants of the strategy	
		V0	V1
Step 1	Certified electricity mix (ESU) 97.78% water, 0.83% wind, 0.73% biomass, 0.66% photovoltaic	X	X
Step 2	Heat pump geothermal	X	X
Step 3	PV P_p = 20 kW, 16000 kWh/a, 20% onsite use		X
Step 4	Building automation Heating C → A		X
Step 5	Minergie-P **Façade:** Rockwool, Thickness 19 cm, U-value 0.15 **Windows**: Wood Standard, G-value 0.55, U-value 0.78		X
Step 6	Low embodied PE and GHG emissions in insulation materials		X

Table 23: The steps of the main strategy and the strategy variant V1.

Calculated results of the strategy variants, shown in Figure 45 and Figure 46 and indicated in Table? in the Annex, allow for stating the following discussion points.

- The PV installation (step 3) does not mitigate significantly GHG emissions because it is done after step 1 and 2 that introduce the use of certified electricity mix and heat pump. The certified electricity mix has a remarkably low GHG emissions factor. However, the mix has a relatively high PE factor. Hence, the installation influences more significantly the primary energy consumption. The yearly costs increase only slightly due to the upfront investment costs which are almost paid off by subsequent energy cost savings. However, in the considered situation PV is not a cost optimal step in terms of GHG emissions mitigation.
- The building automation level of heating is enhanced from the level C to A. This reduces space heating and hot water demand. However, the reduction causes only a minor change in GHG emissions due to the extremely low GHG emissions factor of the certified electricity mix used by the heat pump. PE reduction is comparatively higher. The yearly costs increase since subsequent energy cost savings can't pay off the upfront investment costs.
- A package of insulation measures (façade and windows) with the Minergie-P label is carried out in step 5. This reduces space heating demand. However, this measure even increases slightly GHG emissions due to embodied emissions of insulation materials and an extremely low GHG emissions factor of the certified electricity mix used by the heat pump. PE reductions are comparatively higher. Moreover, the yearly costs increase due to too low energy cost savings.
- The construction design and material choice of the envelope insulation measures (step 5) are chanced to have lower embodied energy and GHG emissions in order to reduce PE use and GHG emissions. Insulation level Minergie-P is dropped in the Minergie level. This change leads to a minor reduction of GHG emissions due to reduced embodied energy and emissions. The yearly costs slightly decrease.

When targeting a GHG emissions reduction target with optimal costs (PE reduction has a second priority) all the steps after the second step only increase the yearly costs, but don't further reduce GHG emissions, and thus would not be included in a cost-optimal GHG strategy. If the certified electricity mix or heat pump cannot be used, the conclusion could be different. Note that other heating systems were studied in the “GHG oriented” strategy (see chapter 3.4.2), demonstrating that the geothermal heat pump leads to the lowest costs with low GHG emissions reduction.

The main target of the strategy was to reach low GHG emissions with a cost optimal solution. The SIA 2040 guide values (6 $kgCO_{2eq}/m^2a$ and 450 MJ/m^2a) are reached in terms of the GHG emissions and PE use with the variant V1. See Figure 45 and Figure 46.

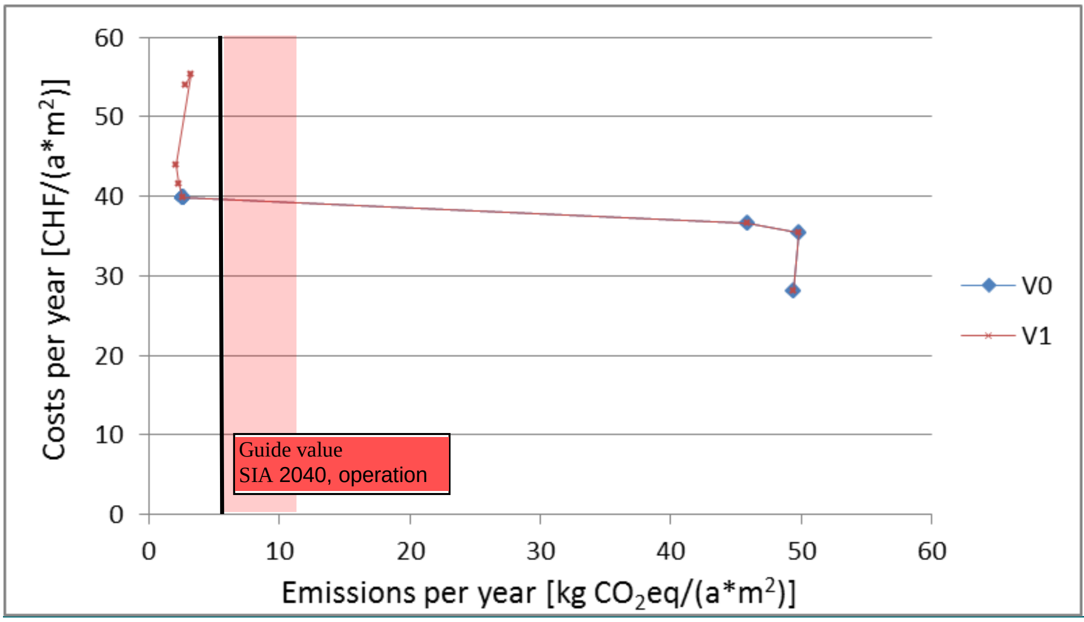

Figure 45: Life cycle costs as a function of GHG emissions due to the strategy steps of the each strategy variant compared to guide value “operation” and “operation+construction” of SIA 2040.

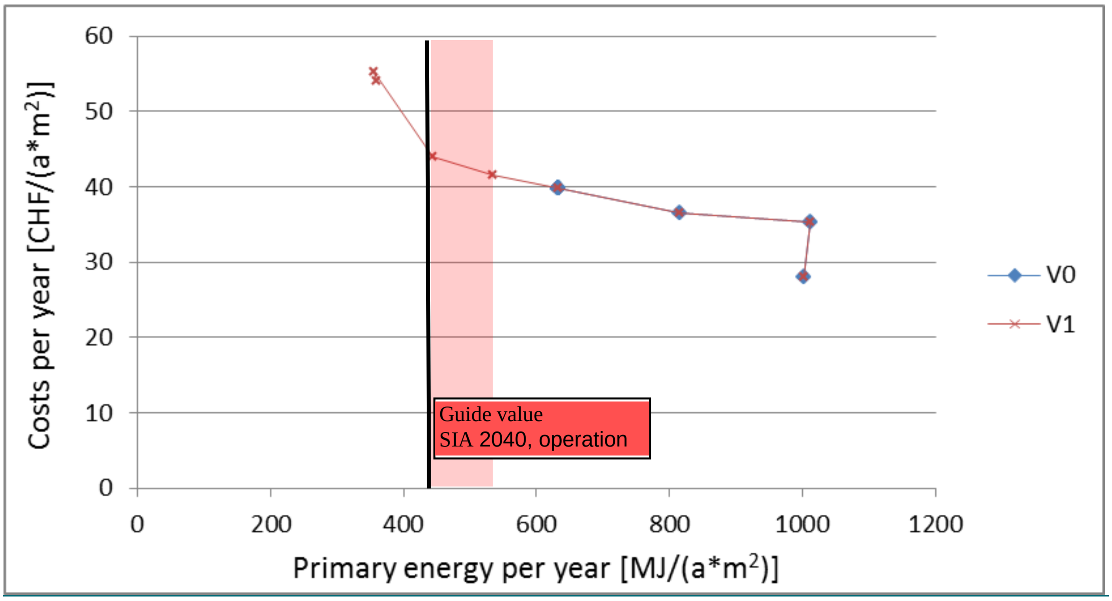

Figure 46: Life cycle costs as a function of PE use due to the strategy steps of the each strategy variant compared to guide value “operation” and “operation+construction” of SIA 2040.

3.6.2 IV.b: targeting PE efficiency increase

The “life cycle cost and PE efficiency optimizer” strategy targeting PE efficiency seeks ambitious environmental goals with the lowest costs. The strategy steps are defined using the results of the “PE oriented” strategy in which the most cost effective steps can be seen. Additionally, two strategy variants are presented: Within the first step different insulation levels are studied. The main strategy and the variants are described in more detail in Table 24 below. First, the results of the main strategy are presented, followed by the results of the different strategy variants similar to the previous strategies.

The results of the "life cycle cost and PE optimizer" main strategy

The results regarding GHG emissions mitigation and PE efficiency increase are represented in Figure 47 and Figure 48, respectively. Allowing illustrating the strategy whose main function is to increase PE efficiency with optimal yearly costs:

Step 1 A comprehensive Minergie-P labelled ventilated façade insulation is undertaken. This measure reduces space heating demand and thus, PE use and GHG emissions. However, the yearly costs are slightly increased due to the investment costs that exceed energy cost savings.

Step 2 Replacing the oil heating system by a district heating system results in a significant reduction of GHG emissions and PE use because of the lower GHG emissions and PE factors. The yearly costs, after implementing the considered step, remain almost constant due to energy cost savings that cover the investment costs.

Step 3 The construction design and material choice of the façade insulation are changed to solutions with lower embodied energy and GHG emissions. Instead of the ventilated glass wool façade insulation a compact EPS insulation is selected. The Minergie-P label is fulfilled. This step slightly decreases GHG emissions and PE use due to reduced embodied energy. Additionally, the yearly costs slightly decrease.

Step 4 Old appliances are replaced by high energy-efficient ones. This change reduces electricity consumption and thus, GHG emissions and PE use. The reduction has a relatively higher impact on PE use due to the high PE factor of the used CH electricity mix. The impact on GHG emissions is lower because of the relatively low GHG emission factor. Additionally, the replacement reduces the yearly costs due to the energy cost savings paying off the upfront investment costs.

Step 5 The PV installation decreases both GHG emissions and PE use due to the on-site use that replaces electricity purchased from the grid, i.e. CH electricity mix which has a relatively high PE factor and GHG emission factor. Additionally, the installation increases only slightly the yearly costs due to the investment costs that are almost compensated by the savings from the on-site use and sale of electricity.

Step 6 The building automation level is enhanced from the level C to A. This enhancement decreases space heating, hot water and electricity consumption. Due to this enhancement GHG emissions and PE use decrease. As compared to GHG the impact is slightly higher regarding PE which is explained by the high PE factor of the used CH electricity mix. However, the yearly costs increase more significantly due to the upfront investment costs and relatively low energy cost savings.

Step 7 The ventilation system with heat recovery reduces GHG emissions and PE use due to reduced space heating demand, but only to a quite small extent. The yearly costs increase significantly due to the fact that investment costs are not paid off by energy cost savings and due to additional operation costs.

As a conclusion the cost optimal strategy with all defined strategy steps has relatively less insulated building envelope parts (only façade although it is Minergie-P level) and an efficient ventilation system with heat recovery. The higher insulation level increases the costs. The most cost effective steps are the fourth, third, second, fifth and first, respectively. Steps S6 (building automation) and S7 (ventilation system) would not be part of a cost-optimal strategy (depending on the GHG mitigation and PE efficiency goal).

In terms of GHG emissions the strategy reaches only the combination guide value for operation and construction (11 $kgCO_{2eq}/m^2a$). However, in terms of PE use the guide value for operation (450 MJ/m^2a) is reached. See Figure 47 and Figure 48.

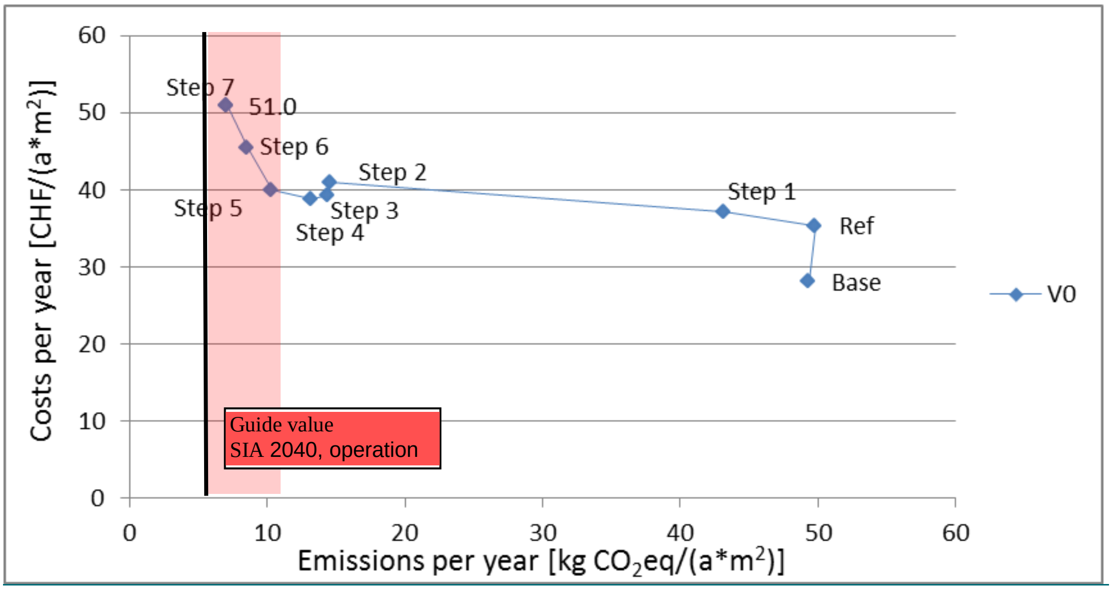

Figure 47: Yearly costs as a function of GHG emissions due to the strategy steps of the “LCC and PE optimizer” strategy compared to guide value “operation” and “operation+construction” of SIA 2040.

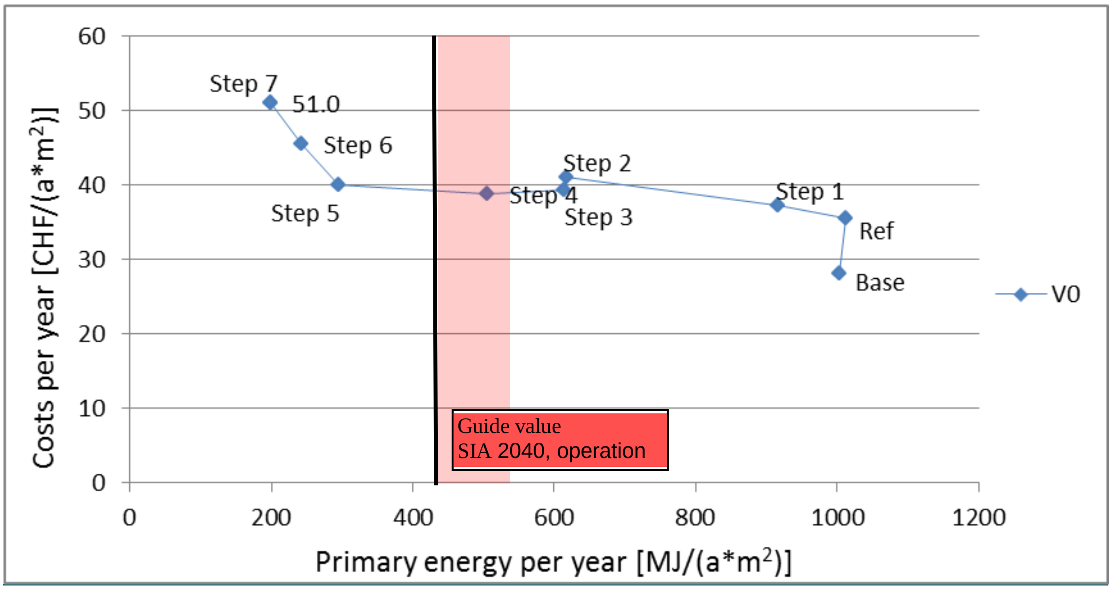

Figure 48: Yearly costs as a function PE efficiency increase due to the strategy steps of the “LCC and PE optimizer” strategy compared to guide value “operation” and “operation+construction” of SIA 2040.

In Figure 49 the yearly costs depending on the steps of the main strategy are illustrated. The costs consist of three parts: energy, capital and maintenance plus operating costs. Energy costs decrease from step to step (except step 2 certified electricity mix), most significantly in steps S4 (appliances) and S5 (PV). However, capital costs rise from step to step (except step 3), most significantly after the fourth step, yielding increasing yearly costs after step 4.

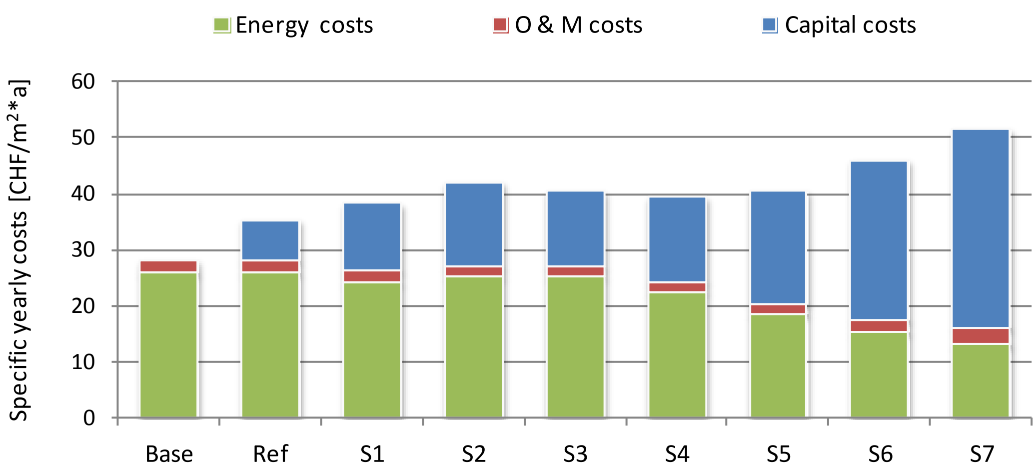

Figure 49: Specific yearly costs development depending on the *“life cycle cost and PE optimizer”* strategy steps.

The strategy variants of the* "life cycle cost and PE optimizer" *strategy

Two different strategy variants V1 and V2 are studied. These variants have a higher envelope insulation level than the main strategy V0. All of the other strategy steps are carried out in the same way as in the main strategy.

		Different variants of the strategy		
		V0	V1	V2
Step 1a	Minergie-P **Façade:** Glass wool, Thickness 19 cm, U-value 0.15	X		
Step 1b	Minergie-P **Façade:** Glass wool, Thickness 19 cm, U-value 0.15 **Windows**: Metal, G-value 0.45, U-value 0.80		X	
Step 1c	Minergie-P **Façade:** Glass wool, Thickness 19 cm, U-value 0.15 **Roof:** Glass wool, Thickness 20 cm, U-value 0.15 **Windows:** Metal, G-value 0.45, U-value 0.80			X
Step 2	District heating Zürich mix 63% waste, 15% wood, 10% gas, 8% oil, 4% geo HP	X	X	X
Step 3	Low embodied PE and GHG emissions in insulation materials	X	X	X
Step 4	Above average efficient electricity services, appliances and lighting	X	X	X
Step 5	PV P_p = 20 kW, 16'000 kWh/a, 20% onsite use	X	X	X
Step 6	Building automation from C to A	X	X	X
Step 7	Ventilation system with heat recovery η_{el} = 0.6 η_{WRG} = 0.90 Ventilated area 75%	X	X	X

Table 24: The steps of the main strategy as well as of the strategy variants V1 and V2.

Calculated results of the strategy variants are shown in Figure 50 and Figure 51 and the numeric values are indicated in Table? in the Annex. Below the results of the strategy variants, compared with the main strategy, are discussed.

- Additional building elements affected by energy-efficient retrofits, such as window replacement and roof insulation, lead to higher costs (particularly caused by the window retrofit) but also to higher PE reduction.
- Replacing the oil heating system by a district heating system yields the highest PE reduction in the main strategy due to the lowest insulation level and the highest heating demand. Nevertheless, significant PE reduction is also reached in the

variants V1 and V2. The costs increase due to upfront investment costs that are not paid off in any of the strategy variants considered here.

- The highest influence of choosing insulation measures with low embodied energy (step 3) occurs in variant V2 due to the highest number of building elements affected by energy-efficient retrofits. Thus, PE use is reduced by materials with low embodied energy, but only to a small extent. Additionally, the LCC costs are slightly reduced.
- In the strategy variants V1 and V2 high energy-efficient appliances and lighting and PV installation reduce PE use to a similar degree as in the main strategy because the insulation level of the building envelope does not influence electricity consumption (in this case no heat pumps are used as a heating system). However, high energy-efficient appliances and lighting reduce also the costs due to energy cost savings. The PV installation increases the costs only slightly due to the upfront investment costs and sufficient subsequent energy cost savings.
- Building automation enhancement from the level C to A and installation of a ventilation system with heat recovery decrease heating demand. Building automation decreases also electricity consumption and thus, it has an impact on the PE use in the variants V1 and V2. In contrast to building automation the ventilation system with heat recovery reduces only heating demand. Hence, this measure does not reduce heating demand significantly due to already well insulated buildings in the variants V2 and V3. The last step adds more costs than benefits.

As a conclusion the main strategy as a whole exhibits about the lower cost-effectiveness than strategy variant V2 without the last two steps. In variant V2 heating demand is already reduced by comprehensive envelope insulation and the last two steps of the main strategy increase relatively more the costs than decrease PE use. Given ambitious PE efficiency goals the cost optimal solution is either to select a minor envelope insulation level and a ventilation system with heat recovery or to invest more in envelope insulation not carrying out steps 6 and 7 (building automation and ventilation system) which, however, leads to lower yearly costs than V0.

The main target of the strategy was to reach better PE efficiency with a cost optimal solution. The guide value of operation for PE use (450 MJ/m^{2}a.) is reached with each strategy variant. However, the guide value of GHG emissions (6 kgCO_{2eq}/m^{2}a) is only reached by V2. The other variants still reach the guide value for operation and construction (11 kgCO_{2eq}/m^{2}a) in terms of the GHG emissions.

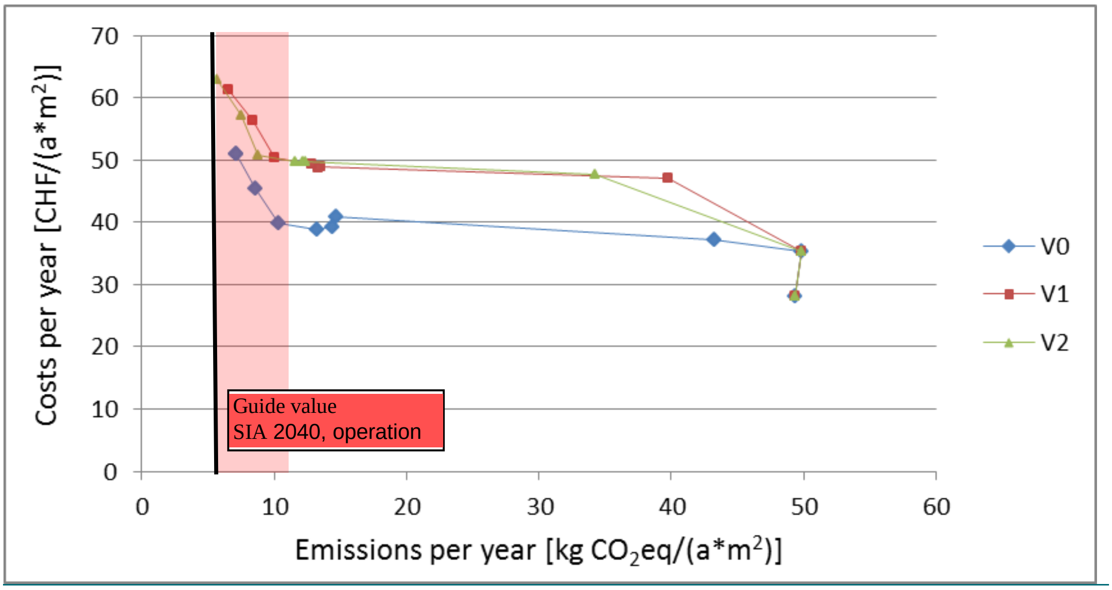

Figure 50: Yearly costs as a function of GHG emissions due to the strategy steps of the each strategy variant compared to guide value “operation” and “operation+construction” of SIA 2040.

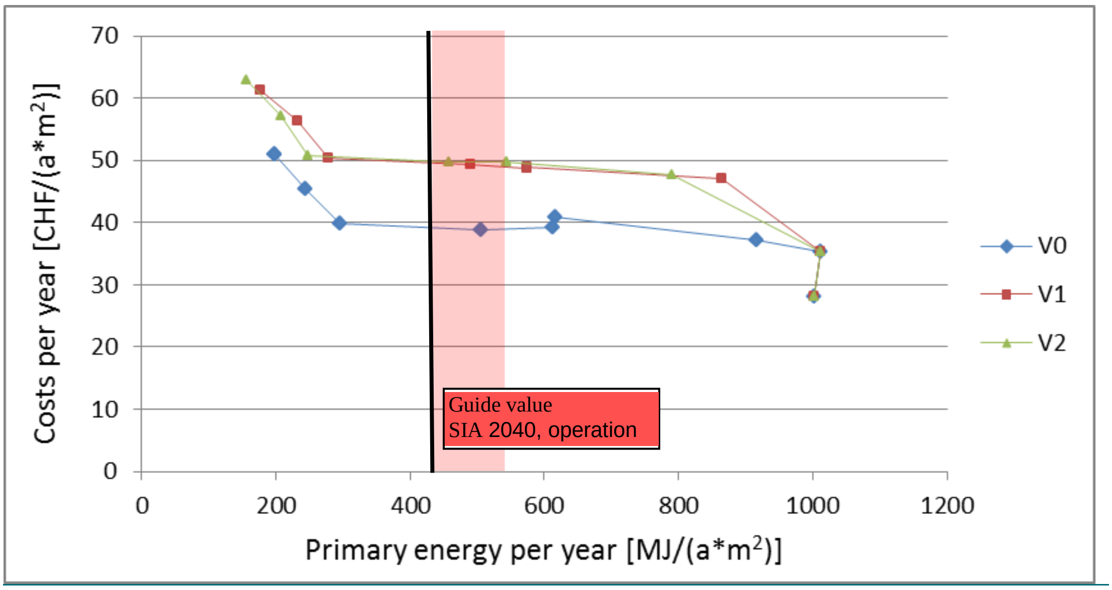

Figure 51: Yearly costs as a function of PE use due to the strategy steps of the each strategy variant compared to guide value “operation” and “operation+construction” of SIA 2040.

3.6.3 IV.c: targeting both GHG and PE

The “life cycle cost optimizer” strategy targeting PE mitigation and PE efficiency seeks ambitious environmental goals with the lowest costs. The strategy steps are defined using the results of the “PE oriented” and “GHG oriented” strategy in which the most cost effective steps can be seen (see chapter 3.4.2 and 3.4.3). Additionally, two strategy variants V1 and V2 are presented. There is a difference between the main strategy and variants within the second step where different insulation levels are studied. Additionally, lower efficiency levels in the sixth and seventh steps are selected for the strategy variant V2 due to the highest efficiency level in the second step. The main strategy and variants are defined below in Table 25. First the results of the main strategy are presented followed by the results of the different strategy variants, similarly to the previous strategies.

The results of the “life cycle cost optimizer targeting both PE and GHG” main strategy

The results regarding GHG emissions mitigation and PE efficiency increase are represented in Figure 52 and Figure 53, respectively. Bearing in mind that the main function of the strategy is to balance GHG mitigation and PE efficiency with optimal life cycle costs, the following discussion points arise:

Step 1 The electricity supply mix is changed from the CH-mix to the certified electricity mix including hydropower, photovoltaic, wind and biomass. The new electricity supply mix has a lower CO_2 content than the CH-mix. Due to this change the GHG emissions are mitigated. Additionally, the primary energy factor is lower than in the CH-mix and thus, PE use is reduced as well. The yearly costs increase slightly because of the higher price of the certified electricity as in the earlier strategies.

Step 2 A comprehensive Minergie-P labelled ventilated façade insulation is undertaken. This measure reduces space heating demand and thus, PE use and GHG emissions. The yearly costs are slightly increased due to the upfront investment costs, entailing similar cost-effectiveness as the previous measure (the curves have about the same steepness).

Step 3 Replacing an oil heating system by a geothermal heat pump mitigates significantly GHG emissions and also the total PE use is reduced, although by a lower extent because of the environmental heat used by the heat pump, which increases PE use. These effects result from the high heating system efficiency and from the certified electricity mix which has low CO_2 content and PE factor. Note that the selection of the heating system is based on the results of the “GHG oriented” strategy (chapter 3.4.2). The yearly costs are increased only slightly due to energy savings caused by the replacement.

Step 4 The PV installation decreases both GHG emissions and PE use due to the on-site use of generated electricity. However, PE use is decreased more significantly. Own electricity generation decreases the amount of purchased CH electricity mix which has a relatively high PE factor and also CO_2 content. Additionally, the installation increases only slightly the yearly costs due to the investment costs that are almost compensated by the savings from the on-site use and sale of electricity.

Step 5 Construction design and material choice of the façade insulation are changed by solutions with lower embodied energy and GHG emissions. Instead of the ventilated glass wool façade insulation a compound EPS insulation is selected. The Minergie-P label is still fulfilled. Due to reduced embodied energy this step slightly decreases GHG emissions and PE use. Additionally, the yearly costs decrease slightly.

Step 6 Appliances and lighting are replaced by high energy-efficient equipment. This change reduces electricity consumption and thus, GHG emissions and PE use. Additionally, the replacement reduces the yearly costs due to energy cost savings.

Step 7 The building automation level is enhanced from the level C to A. This enhancement decreases space heating, hot water and electricity consumption. Thus, the PE use is decreased. However, the yearly costs increase due to high upfront investment costs.

Step 8 The ventilation system with heat recovery reduces PE use due to reduced space heating demand. The extent of the PE reduction depends on the envelope insulation level of the building. The yearly costs are increased due to the investment and maintenance costs.

As a conclusion most of the GHG emissions mitigation results from the three first steps. However, the further steps of the strategy further reduce more significantly PE use. Omitting these further steps (steps 7 and 8) prevents yearly costs increase more significantly than PE reduction and leads to a quite cost effective strategy. The most cost effective step to reduce PE use is step 6 followed by the first, third, fourth and fifth step.

The strategy reaches the SIA guide value for operation (6 $kgCO_{2eq}/m^2a$ and 450 MJ/m^2a) in terms of the GHG emissions and PE use. See Figure 52 and Figure 53.

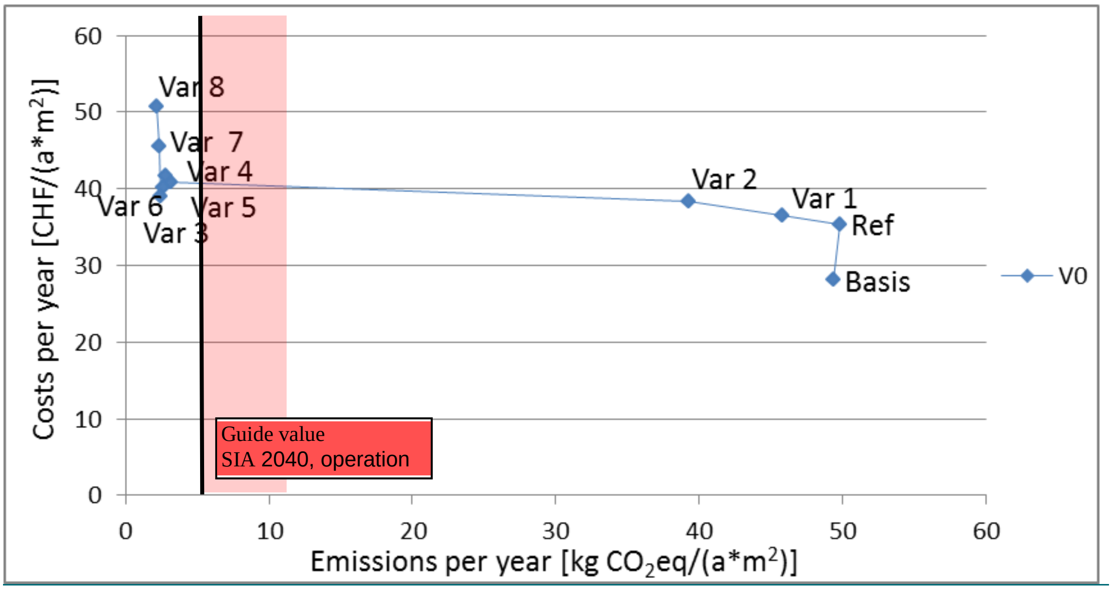

Figure 52: Yearly costs as a function of GHG emissions due to the strategy steps of the "LCC, PE and GHG optimizer" strategy compared to guide value "operation" and "operation+construction" of SIA 2040.

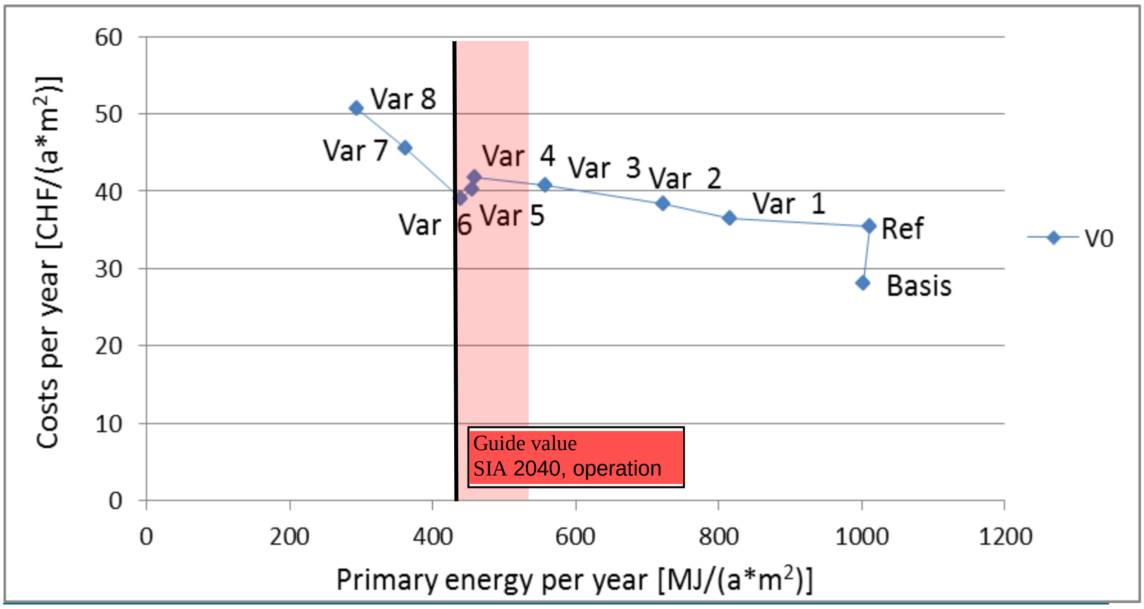

Figure 53: Yearly costs as a function PE efficiency increase due to the strategy steps of the "LCC, PE and GHG optimizer" strategy compared to guide value "operation" and "operation+construction" of SIA 2040.

In Figure 54 the life cycle costs of the main strategy are represented. The costs consist of three parts: energy, capital and maintenance plus operating costs. Energy costs decrease from step 1 to step 7 except in step 5.

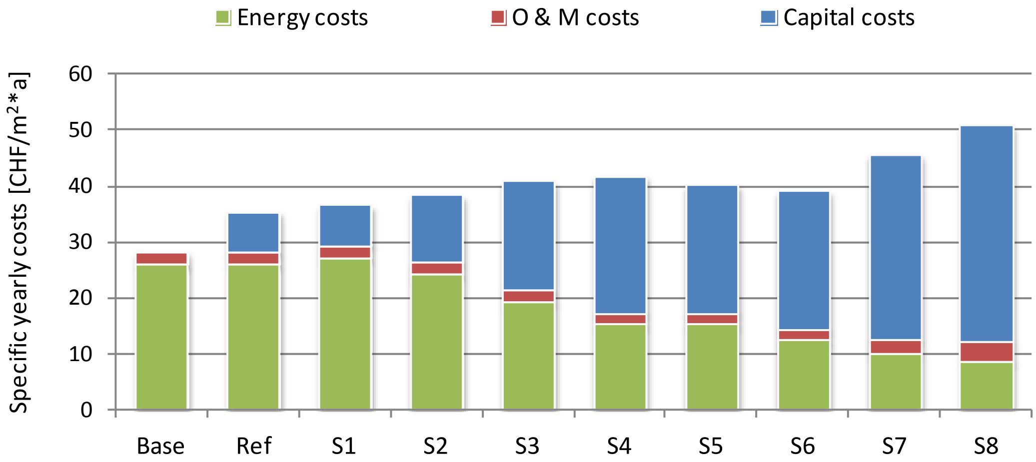

Figure 54: Specific yearly costs development depending on the *"life cycle cost, PE and GHG optimizer"* strategy steps.

The strategy variants of the "life cycle cost optimizer targeting both PE and GHG" strategy

Two different strategy variants V1 and V2 are studied. These variants have a higher envelope insulation level as compared to the main strategy V0. Additionally, variant V2 has a lower efficiency level in the sixth and seventh step due to having the highest efficiency level in the second step.

		Different variants of the strategy		
		V0	V1	V2
Step 1	Certified electricity mix (ESU) 97.78% water, 0.83% wind, 0.73% biomass, 0.66% photovoltaic	X	X	X
Step 2a	Minergie-P **Façade:** Glass wool, Thickness 19 cm, U-value 0.15	X		
Step 2b	Minergie-P **Façade:** Glass wool, Thickness 19 cm, U-value 0.15 **Windows**: Metal, G-value 0.45, U-value 0.80		X	
Step 2c	Minergie-P **Façade:** Glass wool, Thickness 19 cm, U-value 0.15 **Roof:** Glass wool, Thickness 20 cm, U-value 0.15 **Windows:** Metal, G-value 0.45, U-value 0.80			X
Step 3	Heat pump geothermal	X	X	X
Step 4	PV P_p = 20 kW, 16000 kWh/a, 20% onsite use	X	X	X
Step 5	Low embodied PE and GHG emissions in insulation materials	X	X	X
Step 6a	Above average efficient electricity services, appli-ances and lighting	X	X	
Step 6b	Average efficiency level of electricity services, ap-pliances			X
Step 7a	Building automation from C to A	X	X	
Step 7b	Building automation from C to B			X
Step 8	Ventilation system with heat recovery η_{el} = 0.6 η_{WRG} = 0.80 Ventilated area 75%	X	X	X

Table 25: The steps of the main strategy and strategy variants.

The calculation results of the strategy variants are shown in Figure 55 and Figure 56, and the numeric values are indicated in Table? in the Annex. The strategy variants are compared with the main strategy which gives rise to the following statements.

- The higher insulation level in the strategy variants V1 and V2 leads to higher GHG emissions and PE reductions but also to the higher costs. All in all, this difference yields higher costs and the variants are not more cost-effective than the main strategy.
- In variant V2 a lower efficiency level is selected within the sixth and seventh step in order to see if higher insulation costs can be compensated by relatively lower

costs within these two steps. However, strategy variant V2 leads to the highest costs.

As a conclusion the costs optimal strategy to balance GHG mitigation and PE efficiency is to select some but not all building envelope insulation measures, certified electricity mix and heat pump heating system, which consumes low carbon electricity. The main strategy of balancing GHG mitigation and PE efficiency leads to even lower GHG emissions and PE use than GHG and PE oriented strategies.

The all variants of the "LCC optimal, GHG and PE oriented" strategy reach the SIA 2040 guide values for the GHG emissions and PE use for operation (6 $kgCO_{2eq}/m^2a$ and 450 MJ/m^2a).

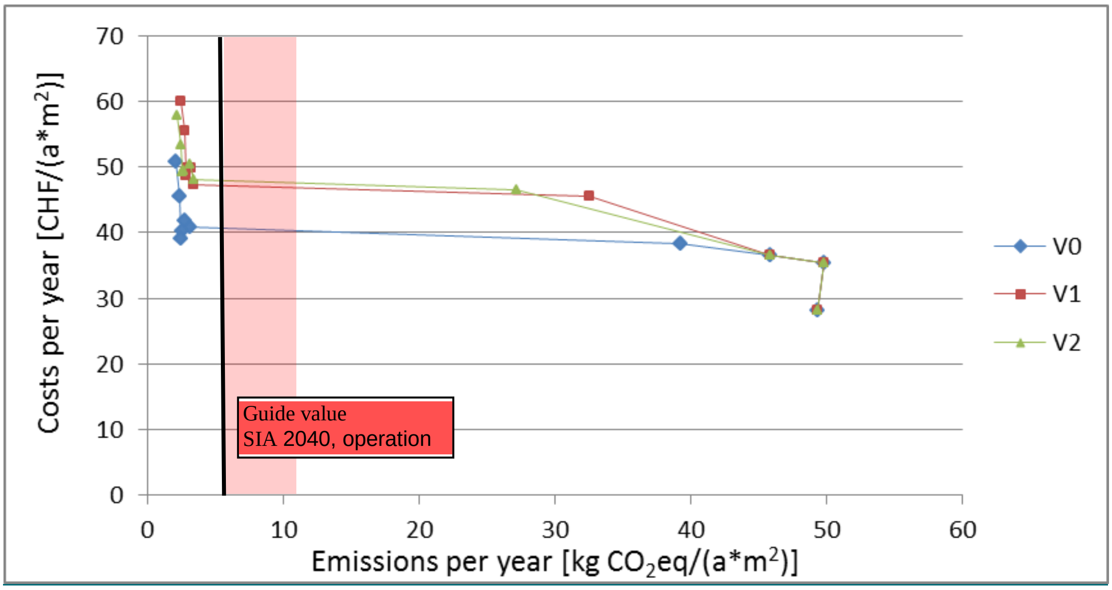

Figure 55: Yearly costs as a function of GHG emissions due to the strategy steps of the each strategy variant compared to guide value "operation" and "operation+construction" of SIA 2040.

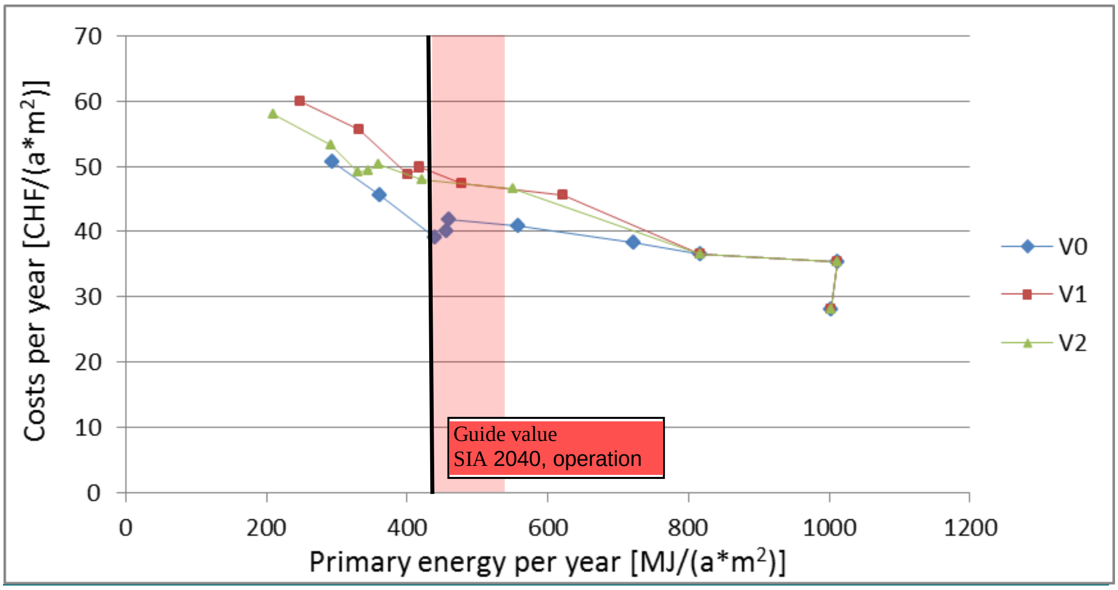

Figure 56: Yearly costs as a function of PE use due to the strategy steps of the each strategy variant compared to guide value "operation" and "operation+construction" of SIA 2040.

3.7 Summarizing results and comparison across the different strategies considered

An overview on the measures that were taken in each step within the different main strategies considered is provided in Table 26. For these measures and strategies the following results are summarized:

- Effect of measures and strategies on GHG emissions and PE use (section 3.7.1)
- Investment costs for each measure for each strategy (section 3.7.2)
- Yearly costs as a function of PE use and GHG emissions are portrayed and analyzed (section 3.7.3).
- Marginal costs as a function of marginal benefits in terms of PE use and GHG emissions are given in section 3.7.4.

	Description	Investment scrooge	Image oriented	GHG oriented	PE oriented	Technology focus	LCC optimal GHG oriented	LCC optimal PE oriented	LCC optimal GHG and PE oriented
M 1	Improvements of the thermal insulation of building envelope (building element and efficiency level)	Step 4 Roof, insulation standard	Step 2 Windows, Minergie Step 6 Façade, Minergie	Step 3 Windows, Minergie-P	Step 1 Façade, Minergie			Step 1 Façade, Minergie-P	Step 2 Façade, Minergie-P
M 2	Choice of energy carrier/ Change of the heating system	Step 2 Gas	Step 5 Wood	Step 1 Wood	Step 3 DH	Step 3 HP geo	Step 2 HP geo	Step 2 DH	Step 3 HP geo
M 3	Implementation of ventilation system with heat recovery functions		Step 4		Step 2	Step 4		Step 7	Step 8
M 4	More efficient electricity services (such as lighting, cooling, appliances) from low efficiency level				Step 5 High efficiency level appliances and lighting	Step 2 Middle efficiency level appliances		Step 4 High efficiency level appliances and lighting	Step 6 High efficiency level appliances and lighting
M 5	Choice of energy supply mix (electricity)	Step 1	Step 3	Step 2			Step 1		Step 1
M 6	Control and regulation of the energy-related building systems and applications from the efficiency level C to B or A. (See explanation in section 2.4.4)	Step 3 C to B		Step 4 C to A, only thermal	Step 6 C to A	Step 1 C to B		Step 6 C to A	Step 7 C to A
M 7	On-site energy production: Implementation of solar thermal panels, PV or wind		Step 1	Step 5	Step 7	Step 5		Step 5	Step 4
M 8	Construction design and material choice with low embodied PE and GHG emissions				Step 4			Step 3	Step 5

Table 26: Summary of strategy steps of each main strategy applied to.the base case building from the construction period 1975-1990.

3.7.1 Effect of measures and strategies in terms of GHG emissions and PE use

As outlined in section 3.1 (page 58) the different measures may have quite different effects, depending on their type, but also depending on the context they are implemented in. To give an overview on the effect of both measures and strategies defined in Figure 57 greenhouse gas emissions are plotted as a function of PE use. Results are analyzed first in terms of measures and then in terms of the strategies as a whole.

Depending on the context, i.e. on the order in which they are taken within its strategy, measure types M1 to M9 have the following effects (see Figure 57):

- M 1 The improvement of the thermal protection by insulation of the building envelope effects in a reduction of the useful (thermal) energy demand and thus in a reduction of final energy demand and related GHG emissions and PE use. In relative terms GHG and PE are reduced similarly, but depending on the type of heating technology and energy carrier either GHG or PE use are affected more. For instance in the GHG oriented strategy almost exclusively PE use is reduced because the heating system was switched to wood beforehand.

- M 2 The choice of the energy carrier and/or the change of the heating system barely changes useful and final energy demand, but mainly reduced GHG emissions. Yet PE use is less affected, especially if total PE (including environmental heat) is considered. Comparing M2 across the different strategies its relative contribution to regarding GHG and PE use reduction is quite similar: the steepness Figure 57 is comparable. Yet two exceptions have to be highlighted: First, the effect of switching from oil to gas is significantly smaller than switching from oil to heat pumps or district heating systems (with low carbon and PE content as assumed here). Second, in the case of switching from oil to wood there is even a slight increase of PE use.
  As compared to M1 the effect of switching from oil to another heating system usually is much larger (if, as assumed here, each element of the building envelope is considered separately and envelope elements are already insulated to a certain point; the relative contribution of a building envelope insulation package applied to a non-retrofitted building of the period 1947 to 1975 would be considerably larger).

- M 3 The implementation of a ventilation system with heat recovery yields in a similar effect as insulation measures (reduction of useful (thermal) energy demand), yet at the price of additional electricity consumption. Thus, as compared to insulation measures, PE use is reduced less. In general terms the effect of M3 is smaller than the effects of M1 and M2.

- M 4 More efficient electricity services (such as lighting, cooling, and appliances) mainly yield in PE reduction, especially if electricity has a low GHG content (see Step 5 of the strategy PE oriented or Step 2 of the strategy Technology focus).

- M 5 The choice of the energy supply mix (electricity, district heating) reduces mainly PE (and GHG, depending on its carbon content), see for instance Step 1 of the strategies Investment scrooge (blue line and rombo marker), LCC optimal GHG oriented (orange line and round marker) and LCC optimal GHG and PE oriented. If electricity demand is already reduced by measures taken beforehand the effect of M5 in smaller (see particularly Step 3 of the Image oriented strategy that adopts electricity production by a PV system).
- M 6 Control and regulation of the energy-related building systems and applications may decrease both useful thermal and electrical energy demand, depending on the type of control measure considered. Thus GHG emissions or PE (e.g. Step 4 of GHG oriented) or both (e.g. Step 3 of investment scrooge) are reduced.
- M 7 The on-site energy production, either in terms of the implementation of solar thermal panels, PV sets or small wind turbines, reduce either thermal energy demand (thus having a similar effect as thermal insulation, see M1) or electricity demand, thus resulting in a similar effect as M4.
- M 8 Construction design and material choice with low embodied PE and GHG emissions affect both PE use and/or GHG emissions, strongly depending on concrete measure considered. The measures considered in this case study yield a rather small effect on GHG emissions, but a small to medium one to PE use (similarly to M4, more efficient appliances and lighting).

Comparing the different strategies across each other it becomes apparent that the guide value of SIA 2040 in terms of GHG emissions is approached or even passed with a limited number of steps. As compared to GHG emissions considerably same or even less steps are needed to satisfy the guideline of SIA 2040 in terms of PE. The latter is the case for four strategies whereas three strategies achieve this requirement completely and one is just over the limit.

Two strategies, that reaches both guide values for GHG and for PE, are the “LCC optimal GHG and PE oriented” and the “LCC optimal GHG oriented” strategy (see Figure 57).

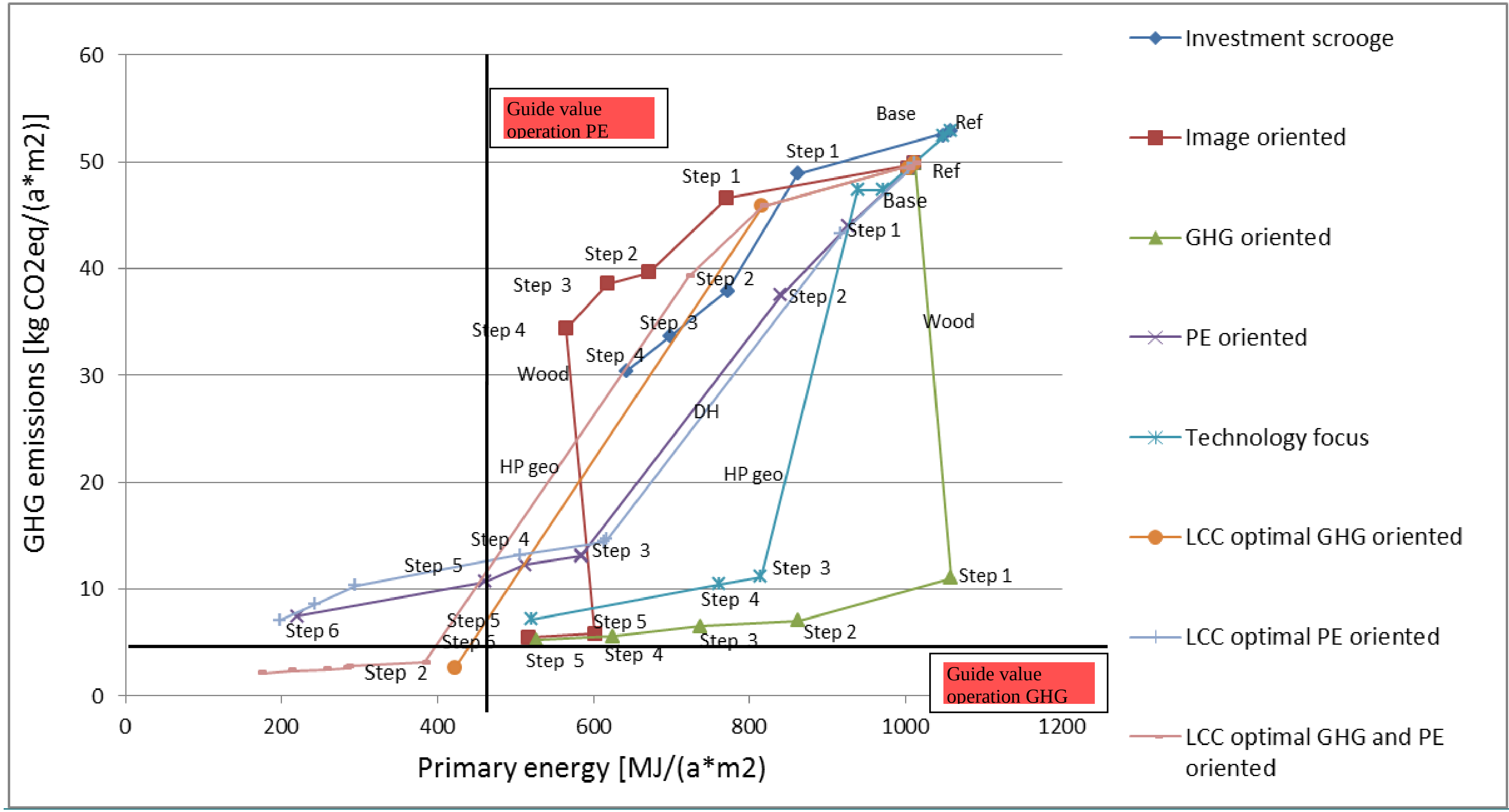

Figure 57: GHG emissions as a function of PE use due to the strategy steps of the each main strategy (applied to the base case building from the construction period 1975-1990) compared to guide value "operation" and "operation+construction" of SIA 2040

3.7.2 Investment costs for each measure and for each strategy

Even though decisions should be based on life cycle costs whenever possible investment costs are an important indicator for building owners and investors. Investment costs are relevant due to owner's budget restrictions and due to financing aspects.

The investment costs per m^2 of floor area (EBF) for each strategy steps are presented in Table 27. With more than 200 CHF/m^2 changing windows is the most cost-intensive of all measures. The other measures of type M1 (thermal insulating of the building envelope) induce investment costs of about 100 CHF/m^2 for each of the elements. The higher insulation level (Minergie-P) results in the significantly higher investment costs than lower level. The standard insulation of the roof results in the lowest investment costs of the considered measures (except electric appliances, see measure type M4).

The investment costs of the heating system (M2) vary between about 50 and 150 CHF/m^2, depending on the type of heating system and on the order of the strategy step. If the investment on the heating system is done after building envelope insulation measures, the size of the heating system can be reduced and the investment decreased. For example, in the image oriented strategy the wood heating system is installed after renewing the windows and the investment costs are 10 CHF/m^2 (about 10%) lower than in the GHG oriented strategy in which the investment on the wood heating system is done before changing the windows. The other measures influence the heating system size as well. For example, the district heating investment costs are 4 CHF/m^2 (about 4%) lower in the PE oriented strategy, due to already executed measures of Minergie façade insulation and the ventilation system with heat recovery, than in the LCC optimal PE oriented strategy in which only the façade is insulated with Minergie-P level. The ventilation system with heat recovery influences also the heating system size. Due to this the investment costs of this step might be different although the ventilation system is the same. Note however that the type of heating system has a larger impact on the investment costs than the order of the strategy step (which is plausible for medium and large heating systems, see Figure 12, page 51). For the considered case of the MFH geothermal heat pumps are most investment-intensive, followed by wood, district heating and gas heating systems needs lowest investments.

Investment costs of the ventilation system (M3) vary between 70 and 100 CHF/m^2, i.e. they are in the same range as most heating systems. Control and regulation measures (M6) are characterized by investment costs varying between about 60 and 100 CHF/m^2. Lowest investments (except for the cases with no investments) are needed for more efficient appliances and lighting (M4). Note that investments increase for these cases (M3, M4 and M6) increase with higher system efficiency. A PV system of the size chosen induces similar investment costs as a ventilation system or control and regulation measures (about 90 CHF/m^2).

However, conversely to the case of heating systems investment costs of M3, M4, M6 and M7 are not depending on other measures.

No investments are needed for M5 (choice of energy mix) and even investment cost savings are resulting from the choice of construction materials chosen (M8).

Comparing the total investment costs of the different main strategies identifies that two strategies clearly induce lower investment costs as the others: the investment scrooge strategy (by design) and LCC optimal GHG oriented strategy. Whereas these two strategies only need investments of about 150 CHF/m^2 the other strategies induce investment costs of about 400 CHF/m^2 (technology focus strategy) to 550 CHF/m^2. The most investment intensive strategy is the image oriented one.

Note that not all of these strategies yield the same impact in terms of GHG mitigation and PE use reduction. Particularly the investment scrooge strategy enables only about half of the effect of most of the other strategies, both in terms of GHG emissions and reduction of PE use.

	Description	Investment scrooge	Image oriented	GHG oriented	PE oriented	Technology focus	LCC optimal GHG oriented	LCC optimal PE oriented	LCC optimal GHG and PE oriented
		CHF/(m^2)	CHF/(m^2)	CHF/(m^2)	CHF/(m^2)	CHF/(m^2)	CHF/(m^2)	CHF/(m^2)	CHF/(m^2)
M 1	Improvements of the thermal protection by insulation of building envelope	48 (roof)	203 (windows) 72 (façade Minergie, last)	202 (windows)	76 (façade Minergie, first)			128 (façade Minergie-P, first)	128 (façade Minergie-P, first)
M 2	Choice of energy carrier/ Change of heating system	52 (gas)	106 (after windows, wood)	116 (before windows, wood)	87 (after insulation, ventilation, DH)	153 (after appliances, automation, HP geo)	145 (no insulation or other, HP geo)	91 (after high insulation level, DH)	127 (after insulation, HP geo)
M 3	Implementation of ventilation system with heat recovery functions		80 η_{el} = 0.4 η_{WRG} = 0.65		96 η_{el} = 0.6 η_{WRG} = 0.80	69 η_{el} = 0.4 η_{WRG} = 0.65		98 η_{el} = 0.6 η_{WRG} = 0.90	81 η_{el} = 0.6 η_{WRG} = 0.80
M 4	More efficient electricity services (such as lighting, cooling, appliances)				16 (high efficiency appliances)	12 (middle efficiency appliances)		20 (high efficiency appliances+lighting)	20 (high efficiency appliances+lighting)
M 5	Choice of energy supply mix (electricity or district heating)	0	0	0			0		0
M 6	Control and regulation of the energy-related building systems and applications	61 C to B		68 C to A, only thermal	101 C to A	59 C to B		101 C to A	101 C to A
M 7	On-site energy production: Implementation of PV		87	87	87	87		87	87
M 8	Construction design & material choice with low embodied PE and GHG emissions				-7			-56	-56
All		161	551	473	460	394	145	481	507

Table 27: Specific investment costs of each measure of each main strategy applied to.the base case building from the construction period 1975-1990.

3.7.3 Yearly costs as a function of PE use and GHG emissions

The results of each considered main strategies are summarized in Figure 58 and Figure 59 regarding to GHG mitigation and PE use, respectively. To interpret the results it is emphasized to keep in mind that the base case building used in the strategy calculations is assumed to be from the construction period 1976 – 1990 which implies that façade and roof are already insulated to a certain (low) extent (Table 16). Moreover it is assumed that windows were replaced in the second half of the 1990s. Also it should be noted that GHG emissions and PE use (and to a certain extent also the yearly costs) are higher in the base and reference building for the “investment scrooge” and “technology focus” strategies due to missing basement insulation which in the case of environmental friendly strategies was undertaken already in the past, thus not entailing any investment costs for this measure for these latter cases, but for the former ones.

Against the background of the chosen building the outcome of the different strategies can be characterized and summarized as follows:

— Most of the strategies have a slightly increasing trend in terms of the costs-GHG and costs-PE relationship in the first steps of the strategies. A slightly increase curve as a function of **lower** GHG emissions and PE use (i.e. from the right to the left of the Figures) means that the measures are not cost-effective, but almost. Economically viable measures are characterized by decreasing curves (or negative marginal costs in Table 28 and in Table 29). Yet most of the strategies yield in a steep increase of the curves in terms of the last few steps within a given strategies. Often, these last steps yield only minor environmental improvements, which is (also) explained be interaction effects: the measures taken first are tapping large parts of the potential already.

— The “investment scrooge” strategy has a similar costs-GHG and costs-PE course as most of the other strategies, but is less comprehensive in terms of potential measures. It thus results in the poorest GHG emissions and second poorest total PE reduction.

— The environmental friendly “image oriented” strategy starts with similar yearly costs as other strategies in the first few steps, but is characterized with highest yearly costs if all steps are considered. Particularly the installation of a ventilation system to achieve the Minergie label and the choice for a wood heating system would increase yearly costs (in the context of the measures taken in the previous steps).

— In the “GHG oriented” strategy two measures namely using wood instead of oil and using low-carbon electricity mitigate GHG emissions effectively. Subsequent measures yield relatively high marginal GHG mitigation costs and are rather useful to increase PE efficiency. In terms of PE efficiency, the most cost effective steps are to change the electricity mix from CH mix to certified electricity mix (Step 2) and to install PV (Step 5). Regarding GHG emission mitigation substituting oil for wood is most cost-effective (Step 1) yielding a large mitigation effect.

- In the “PE oriented” strategy a district heating system reduces significantly GHG emissions and PE use compared to the oil heating system. Additionally, the PV installation (step 7), efficient electricity services (step 5) and envelope insulation (step 1) reduce effectively PE use. The steps 1, 3, 5 and 7 (see Table 26) are the most cost effective steps due to the least steep increase in the yearly costs. The other steps are not cost effective
- Interestingly, the “technology focus” strategy reaches a bit lower total PE decrease (includes also the environmental heat) than “investment scrooge”. This is the poorest PE reduction of the strategies. However, GHG emissions are mitigated significantly more effectively in the “technology focus” strategy due to a heat pump heating system instead of gas heating system.
- The “LCC optimal GHG oriented” strategy mitigates GHG emissions more cost effectively than the “GHG oriented” strategy due to heat pump heating system instead of wood heating system. The steps of the “LCC optimal GHG oriented” strategy are reduced compared to the “GHG oriented” strategy because the last steps in the “GHG oriented” strategy increase more the yearly costs than reduce GHG emissions. However, the total PE reduction is at the same level than in the “Investment scrooge” strategy.
- The “LCC optimal PE oriented” strategy reduces PE use only slightly more than the “PE oriented” strategy due to including also lighting (see Table 26) to high efficiency electricity service.
- The “LCC optimal PE and GHG oriented” strategy results in the high GHG emissions mitigation and PE efficiency. Finally, the yearly costs are at the same level than within the “Investment scrooge”, “PE oriented”, “Technology focus” and “LCC optimal PE oriented” strategies.
- Three levels of the yearly costs can be seen in Figure 58 and Figure 59. The highest yearly costs are resulted in the “Image oriented” and “GHG oriented” strategies. The strategies of “Investment scrooge”, “PE oriented”, “Technology focus” and “LCC optimal PE oriented” results in the medium level costs. The lowest yearly cots level is reached in the “LCC optimal GHG oriented” strategy (when stopping after Step 6).
- In terms of GHG emissions and PE use the most cost effective strategy is “LCC optimal GHG oriented” which has the least steep curve. In terms of GHG emissions the cost effective steps (mainly changing a heating system) are also in the “PE oriented”, “technology focus”, “LCC optimal PE oriented” and “LCC optimal GHG and PE oriented” strategies.

All the strategies reduce significantly GHG emissions excluding the “investment scrooge” strategy in which only about 50% reduction is reached. The highest PE efficiency increase is reached in the “LCC optimal GHG and PE oriented” strategy followed by the “LCC optimal PE oriented” strategy. The lowest PE decrease is caused in the “investment scrooge” strategy.

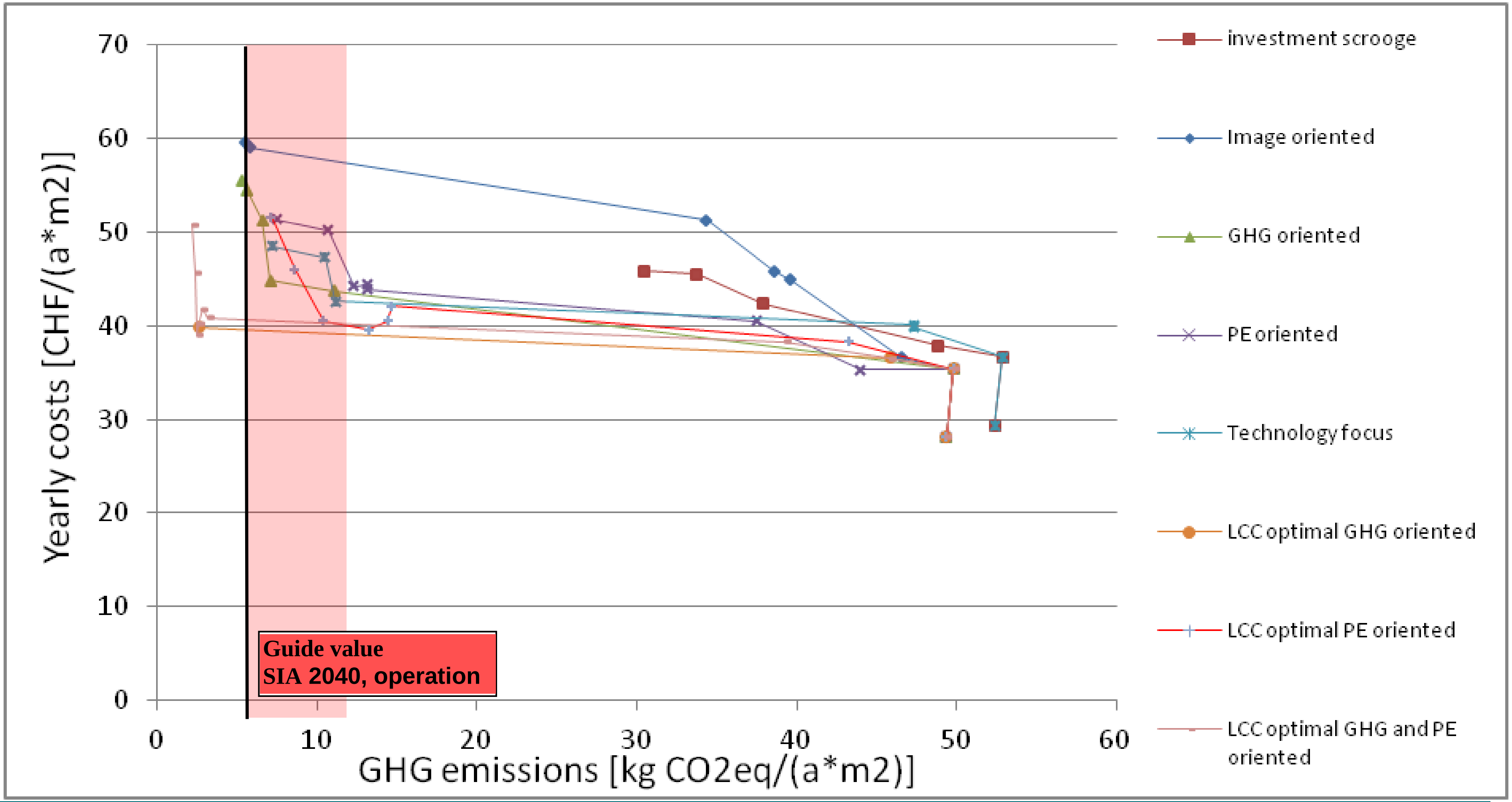

Figure 58: Yearly costs as a function of GHG emissions due to the strategy steps of the each main strategy (applied to the base case building from the construction period 1975-1990) compared to guide value “operation” and “operation+construction” of SIA 2040.

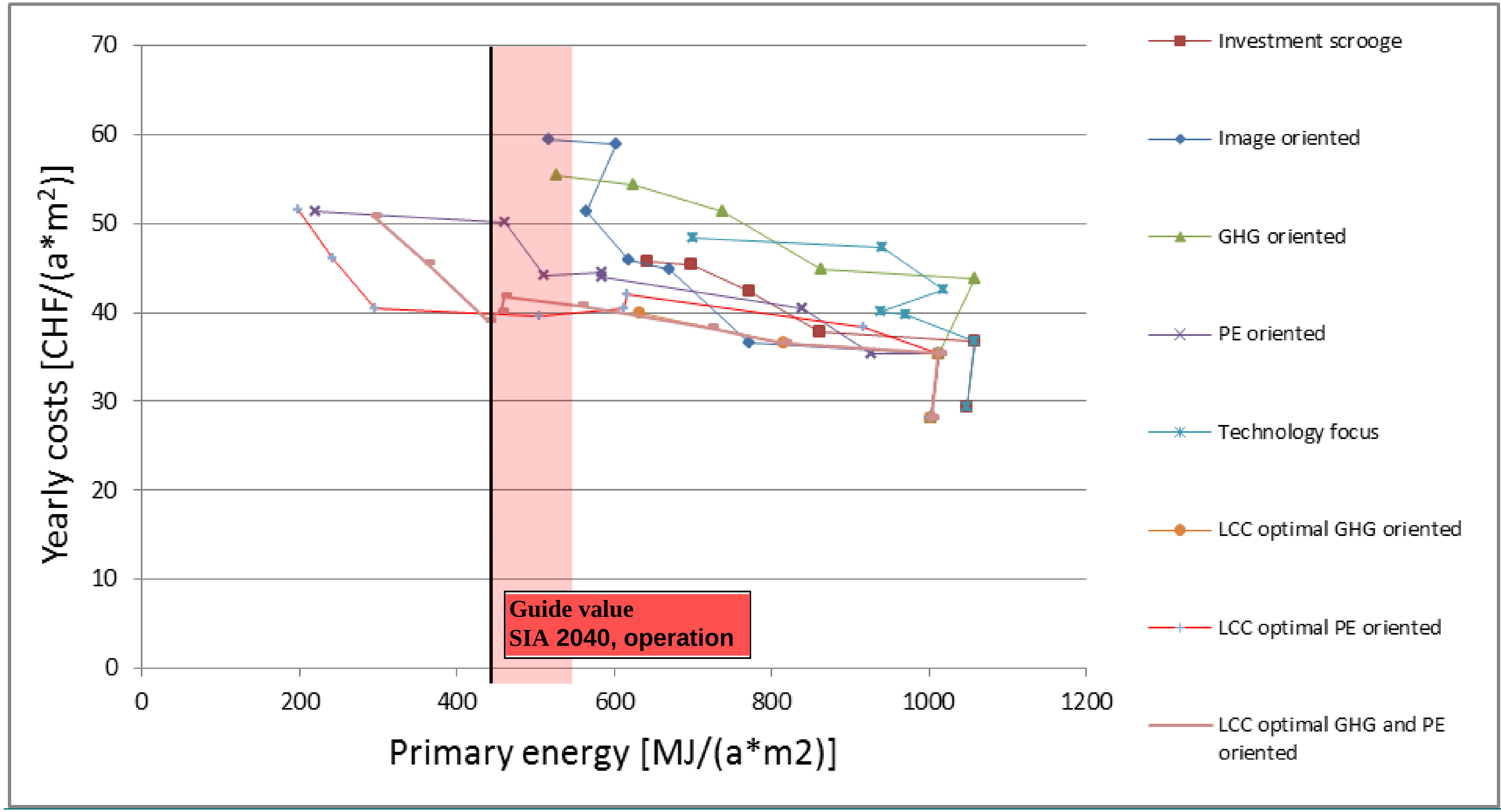

Figure 59: Yearly costs as a function of PE use due to the strategy steps of the each main strategy (applied to the base case building from the construction period 1975-1990) compared to guide value “operation” and “operation+construction” of SIA 2040

3.7.4 Marginal costs as a function of marginal benefits in terms of GHG emissions and PE use

By deliberate definition of the strategies a certain type of measure, for instance insulation of the envelope (M1), is taken either quite in the beginning of the strategy (e.g. M1 in the PE oriented strategy), in the middle or rather at the end of all steps within a certain strategy (e.g. part of M1 in the image oriented strategy), see Table 26 for an overview.

With the chosen set-up, that measures are implemented in a different order across different strategies, it becomes possible to estimate the marginal costs and marginal benefits (expressed as saved GHG emissions and PE use per m2 of floor area respectively) in quite different contexts.

The marginal costs and benefit of each measure in terms of GHG mitigation and PE efficiency increase within the different strategies are indicated in Table 28 and Table 29. In fact these figures are portraying partly the same information as Figure 58 and Figure 59, but in a different form: marginal costs Table 28 and Table 29 represent the derivative of the curves in Figure 58 and Figure 59, i.e. in steepness of each linear segment.

Regarding greenhouse gas emissions the following findings regarding marginal mitigation costs and specific GHG mitigation (Table 28) can be stated:

— M 1, Improvements of the thermal protection by insulation of building envelope: Mitigation costs vary greatly across different strategies, depending on the order this measure is taken, i.e. depending on the type of heating system in place, and thus the carbon-intensity of the final energy used. Mitigation costs are either slightly negative (e.g. both GHG emissions and costs are saved simultaneously), range between 100 to 300 CHF per t of CO_{2eq} but might also largely exceed 500 CHF per t of CO_{2eq} (particularly if the heating system has a low carbon-intensity).

— M 2, Choice of energy carrier / change in the heating system: substituting heat pumps or district heating with low PE and carbon content for fossil energy entails GHG mitigation costs of 30 to 50 CHF per t of CO_{2eq}. In the case of gas or wood heating system GHG mitigation costs are 200 to 500 CHF per t of CO_{2eq}.

— M 3, Implementation of ventilation system with heat recovery functions: GHG mitigation costs of ventilation systems are quite high (more than 800 CHF per t of CO_{2eq} in all the strategies considered) if not a part costs is allocated further benefits such as increased comfort of living (increased indoor air quality, protection against external noise).

— M 4, More efficient electricity related services (such as lighting, cooling, appliances): marginal costs of GHG emissions mitigation are mostly negative (i.e. life-cycle-costs are reduced while GHG emissions are mitigated), except for the case “Technology focus” strategy where efficiency level of appliances is increased only from low to middle level.

— M 5, Choice of energy supply mix (electricity or district heating): GHG mitigation costs vary between 290 and 900 CHF per t of CO_{2eq}; the latter value applies for the situation in which electricity is already partly produced on-site.

— M 6, Control and regulation of the energy-related building systems and applications with building automation systems: GHG mitigation costs are rather high, i.e. more than 500 CHF per t of CO_{2eq}. Mitigation costs of M6 are particularly high if the heating system has low-carbon intensity.

— M 7, On-site energy production: Implementation of solar thermal panels, PV or wind: given the assumed costs of PV systems GHG mitigation costs are estimated to 350 CHF per t of CO_{2eq}.

— M 8, Construction design and material choice with low embodied PE and GHG emissions: GHG mitigation costs vary greatly between plus and minus several thousand CHF per t of CO_{2eq}. Note that marginal benefit of this measure is rather low.

Regarding primary energy use the following findings regarding marginal efficiency costs and specific reductions of primary energy consumption (Table 29) can be stated:

— M 1, Improvements of the thermal protection by insulation of building envelope (comprising roof insulation, better windows, façade insulation or the combination of façade insulation and better windows):
Primary energy efficiency costs vary between 0.6 and 2.0 Rp./MJ[14], except for the façade insulation in the case of the PE oriented strategy which is about economical (only if it is done as the first step and not having replaced the oil heating system yet). For insulation measures achieved PE reductions as well as marginal costs of PE reductions depend on the order the measure is placed in the sequence of steps. If primary energy use is previously reduced by a better heating system with renewable energy or low PE content the PE reduction costs of insulation measures are higher than the insulation measure is carried out first. PE reductions range from (0) or 55 – 227 MJ/m^2a

— M 2, Choice of energy carrier / Change in the heating system (change from oil heating to gas, wood, geothermal heat pump or district heating system):
Primary energy reduction costs vary between 0.6 and 23.0 Rp./MJ. Employment of district heat and geothermal heat pumps is almost economical if renewable electricity is used (1.8 – 1.5 Rp./MJ). If the used electricity has high PE content, PE is not mitigated due to the influence of the environmental heat use. The change to a gas boiler yields higher PE reduction costs of 5 Rp./MJ while in the case of wood boilers PE consumption is even increased. PE reductions range from -46 to 400 MJ/m^2 a.

— M 3, Implementation of a ventilation system with heat recovery functions:
PE reduction by ventilation system with heat recovery yields rather high marginal costs if costs are not split to take additional benefits into account. PE reduction costs

[14] Multiply 1 Rp./MJ with a factor of 3.6 to obtain Rp./kWh

are between 6.0 and 19 Rp./MJ, again depending on the heating system, typically yielding highest PE reduction costs in the case of the image oriented strategy (oil boiler not replaced yet). PE reductions are between 27 and 113 MJ/m^2 a.

- M 4, More efficient electricity services (such as lighting, cooling, appliances):
  These efficiency measures are economical viable or just about economical viable (i.e. quite cost-effective): PE reduction costs range from -4 to 0.7 Rp./MJ and possible PE reductions are 28 – 108 MJ/m^2 at the upper boundary with PE reduction costs of 0.7 Rp./kWh.
- M 5, Choice of energy supply mix (electricity or district heating):
  The costs for reduced PE consumption by using a better energy supply mix are nearly economically viable and range from 0.6 to 1.9 Rp./MJ. PE reductions achieved are 53 – 475 MJ/m^2 a.
- M 6, Control and regulation of the energy-related building systems and applications:
  Achieved PE reductions and resulting PE reduction costs of control and regulation measures depend on the other measures already realized and on the energy performance of the building when equipped with such control devices. The assumed strategies yield PE reduction costs of 3.0 – 20 Rp./MJ. Resulting PE reductions are between 32 and 112 MJ/m^2 a.
- M 7, On-site energy production: Implementation of solar thermal panels, PV or wind:
  The costs of a reducing PE consumption by on-site energy production are near economic viability. They range from 0.5 to 1.0 Rp./MJ. Achieved PE reductions are 98 - 241 MJ/m^2 a.
- M 8, Construction design and material choice with low embodied PE and GHG emissions:
  Low embodied energy measures play a minor role in the three strategies in which this measure is chosen. PE reductions are very small (0.1 – 4 MJ/m^2 a) and the measures are economically viable in the case of LCC optimal PE oriented and LCC optimal PE and GHG oriented strategies. For the case of the PE oriented strategy the PE reduction is only 0.1 MJ/m^2 and therefore not economically viable (5.53 $CHF/MJ/m^2 a$).

Measure	Description	Investment scrooge		Image oriented		GHG oriented		PE oriented		Technology focus		LCC optimal GHG oriented		LCC optimal PE oriented		LCC optimal GHG and PE oriented	
		CHF/kg CO_{2eq}	$kgCO_{2eq}/(m^2a)$	CHF/kg CO_{2eq}	$kgCO_{2eq}/(m^2a)$	CHF/kg CO_{2eq}	$kgCO_{2eq}/(m^2a)$	CHF/kg CO_{2eq}	$kgCO_{2eq}/(m^2a)$	CHF/kg CO_{2eq}	$kgCO_{2eq}/(m^2a)$	CHF/kg CO_{2eq}	$kgCO_{2eq}/(m^2a)$	CHF/kg CO_{2eq}	$kgCO_{2eq}/(m^2a)$	CHF/kg CO_{2eq}	$kgCO_{2eq}/(m^2a)$
M 1	Improvements of the thermal insulation of building envelope	0.10	3.3	1.20 1.40	6.9 0.4	12.47	0.5	-0.007	5.8					0.27	6.6	0.27	6.6
M 2	Choice of energy carrier/ Change of heating system	0.41	11.0	0.27	28.5	0.21	38.8	0.14	24.3	0.07	36.2	0.08	43.2	0.13	28.6	0.07	36.1
M 3	Implementation of ventilation system with heat recovery functions			1.29	4.2			0.79	6.5	6.83	0.7			3.67	1.5	23.52	0.2
M 4	More efficient electricity services (such as lighting, cooling, appliances)							- 0.23	0.8	8.04	0.03			- 0.46	1.2	- 11.23	0.1
M 5	Choice of energy supply mix (electricity or district heating)	0.29	4.0	0.91	1.1	0.29	4.0					0.29	4.0			0.29	4.0
M 6	Control and regulation of the energy-related building systems and applications	0.74	4.2			3.33	0.9	3.8	1.6	0.57	5.5			3.16	1.8	57.42	0.1
M 7	On-site energy production: Implementation of solar thermal panels, PV or wind			0.36	3.3	2.86	0.3	0.36	3.3	0.36	3.3			0.41	2.9	2.86	0.3
M 8	Construction design & material choice with low embodied PE and GHG emissions							6.97	0.1					- 7.50	0.2	- 7.50	0.2

Table 28: Marginal costs of GHG mitigation (CHF/kgCO_{2eq}) and marginal benefit (kgCO_{2eq}/(m^2a)) of the measures within each strategy the applied to the base case building from the construction period 1975-1990.

Measure	Description	Investment scrooge		Image oriented		GHG oriented		PE oriented		Technology focus		LCC optimal GHG oriented		LCC optimal PE oriented		LCC optimal GHG and PE oriented	
		CHF/ MJ	MJ/ (m^2a)	CHF/ MJ	MJ/ (m^2a)	CHF/ MJ	MJ/ (m^2a)	CHF/ MJ	MJ/ (m^2a)	CHF/ MJ	MJ/ (m^2a)	CHF/ MJ	MJ/ (m^2a)	CHF/ MJ	MJ/ (m^2a)	CHF/ MJ	MJ/ (m^2a)
M 1	Improvements of the thermal insulation of building envelope	0.006	56	0.08 0.006	100 84	0.05	125	-0.0005	85					0.02	95	0.02	95
M 2	Choice of energy carrier/ Change of the heating system	0.05	90	0.21	- 37	0.18	- 46	0.013	256	- 0.032	-80	0.018	183	0.013	300	0.015	164
M 3	Implementation of ventilation system with heat recovery functions			0.10	53			0.06	86	0.10	45			0.12	44	0.19	27
M 4	More efficient electricity services (such as lighting, cooling, appliances)							- 0.003	72	0.007	32			- 0.005	107	- 0.04	28
M 5	Choice of energy supply mix (electricity or district heating)	0.006	195	0.019	53	0.006	195					0.006	195			0.006	195
M 6	Control and regulation of the energy-related building systems and applications	0.04	73			0.03	112	0.12	51	0.04	87			0.11	52	0.20	32
M 7	On-site energy production: Implementation of solar thermal panels, PV or wind			0.005	241	0.01	98	0.005	241	0.005	241			0.005	210	0.01	98
M 8	Construction design and material choice with low embodied PE and GHG emissions							5.53	0.09					- 0.41	4	- 0.41	4

Table 29: The marginal costs of PE efficiency increase (CHF/MJ) and marginal PE benefit (MJ_{PE}/m^2) of the measures within each strategy applied to the (applied to the base case building from the construction period 1975-1990)

4 Conclusions and recommendations for building owners and investors in existing residential MFH

4.1 Conclusions

From the calculation results of the various generic strategies applied to a type of an existing multi-family houses (of the construction period 1975 to 1990) which is already partly retrofitted (windows) and from calculations performed within the context of the international part of the INSPIRE project (Jakob et al. 2014) the following conclusions may be derived:

- Some of the measures are hardly affected by other measures taken previously which makes it easier to summarize their effect:
    - Given the decreased prices that reduce costs of PV installations and assuming a net metering regime PV is recommended due to quite favorable cost effectiveness (as compared to other measures). The PV installation reduces strongly PE use and GHG if the on-site use share can be maximized and the grid electricity substituted is PE and GHG emissions intensive. In this case the electricity mix is not taken into account as a measure. If the electricity mix is taken into account as a measure, the cost effectiveness of the PV installation is decreased. Thus, only one out of these two measures is recommended to be undertaken.
    - The selection of lower embodied energy content in the envelope insulation measures reduces only slightly GHG emissions and PE use
- Substantial interaction effects occur between the different strategic approaches of the building envelope (thermal improvements of appropriate elements and windows through insulation and replacement), the installation of building automation, the change of heating systems and the choice of low-carbon and/or low-PE energy carriers (e.g. certified electricity or district heating from waste energy). This implies that the marginal benefits and thus, the cost-effectiveness of such measures are conditioned to the situation (i.e. to the measures taken previously). Results may be summarized as follows:
    - Highly efficient electricity services (such as lighting and appliances) reduce electricity consumption, primary energy use and – in most cases – GHG emissions cost effectively or even economically viable, basically independent from other types of measures taken within a certain strategy. However, their effect depends strongly on the PE and GHG emissions content of the used electricity mix. The higher the PE and GHG emissions content the stronger the effect on the PE and GHG emissions reduction.
    - The thermal improvements of the building envelope are cost effective if the energy carrier is primary energy and GHG intensive and especially in case of low efficiency of the existing envelope. However, the measure with the highest envelope effi-

ciency (the type of the insulation: Minergie-P) and a big number of insulated envelope elements increases the yearly costs significantly. See the “LCC optimal, GHG and PE oriented” strategy variants on the pages 110 – 112.

 - Implementation of a ventilation system with a heat recovery function reduces heating demand and thus, PE use and GHG emissions are reduced as well if the energy carrier is PE and GHG emissions intensive. However, the installation is not cost effective in terms of energy related benefits only. It leads to other benefits, such as thermal and living comfort (air quality, noise protection) as well as moisture and mold prevention. Due to this the part of the costs can be allocated to the additional benefits and property validation.
 - A heat pump heating system leads to the high system efficiency and GHG emissions are reduced. The maximal reduction can be achieved if the certified low carbon and low PE content electricity supply mix is used. If PE content of the electricity mix is high, then the total PE use is increase due to the used environmental heat. The heat pump heating system increases slightly the yearly costs but the reduction effect on PE use and GHG emissions is significant. The heat pump heating system has relatively stronger influence to PE and GHG emissions reduction if the building is less insulated. However, in this case the yearly costs are slightly higher than in a better insulated building because of a heating system with higher power is required. See the “LCC optimal, GHG and PE oriented” strategy variants on the page 110 – 112.

- Even within the same type of measures (e.g. heating system distribution) the effect of some of the measures may be quite different depending on whether GHG emissions or PE use is considered.
 - District heating systems reduce GHG emissions and PE use significantly depending on the heat sources (the reduction depends significantly on the production mix). However, a wood heating system predominantly reduces GHG emissions whereas total PE use is only marginally decreased or may even increase when compared to an efficient oil or gas heating system. The effect of heat pumps depends on the electricity mix considered. If the electricity mix is PE and GHG emissions intensive (and not changed simultaneously with a HP), the reduction effect is higher than in the case of low intensity. However, if electricity mix is changed together with a switch to HP to a low intensity, then the effect of the combined measures (HP+electricity mix) is large.
 - Efficient appliances and lighting affects predominantly PE use, especially if low-carbon and high-PE electricity is used. (e.g. nuclear power or biomass)
- Appropriate selection of retrofit measures can result in high GHG emission mitigation and PE use reduction with the same life cycle costs than “inappropriate” selection of measures. (See “investment scrooge” and “LCC optimal GHG and PE oriented” strategies in Figure 58 and Figure 59). **Hence, building owners and investors have a**

certain degree of freedom to achieve their strategic goals in terms of PE and GHG emission.

- The effect (in terms of GHG emissions mitigation and/or reduction of PE use) is quite different among different types of measures:
  - Changing the energy carrier of the heating system usually yields either a quite high impact on both GHG emissions mitigation and total PE use or has an almost no impact on both indicators but especially on primary energy use (e.g. in the case of a change to wood as renewable energy carrier) or in the case of using nuclear or fossil based electricity in HP: Rarely there is a medium impact)
  - The selection of lower embodied energy content in the envelope insulation measures reduces only slightly GHG emissions and PE use.
  - Most of the other measures yield a medium marginal effect in terms of GHG emissions and PE use reduction. However, the PV installations result in a high marginal effect and in terms of GHG emissions biomass results also in a high marginal effect.

4.2 Recommendations

The general retrofitting recommendations depend strongly on the goal of the retrofit strategy. There are different measures that are recommended to undertake depending on whether the goal is to reduce PE use, GHG emissions or both. Recommendations to retrofit existing multi-family houses (of the construction period 1975 to 1990 which are already partly retrofitted (windows), may be derived from the calculation results and from the conclusions above:

To achieve more or less ambitious GHG mitigation and/or PE efficiency goals different strategies may be adopted. Usually some few measures yield a considerable effect with quite reasonable cost-effectiveness. The “last” steps in the most of the strategies investigated are much less cost-effective and rather not recommended from an economic perspective. Thus, it is recommended to select the measure carefully.

General recommendations

In terms of individual measures the following recommendations can be stated:

- Highly efficient electricity services (such as lighting and appliances) are recommended with almost no reservation as they are cost effective or even economically viable.
- The building envelope thermal improvements (insulation and replacement of windows) are cost effective if the energy carrier is primary energy and GHG intensive and especially in the case of a low efficiency of the existing building envelope. Additionally, it is recommended to select carefully the building envelope parts to be insulated(mainly those that are not insulated at all) and efficiency level. The Minergie-P efficiency level leads to the relatively low additional benefit and high marginal costs if

compared to Minergie. Thus, it is recommended to invest into renewable energy use or a green electricity mix, etc. that have constant or at least less increasing marginal costs than insulation.

- Implementation of a ventilation system with heat recovery function is not recommended from cost-effectiveness point of view, but, from a normative point of view, if far reaching goals should be achieved, such systems are recommended notably in cases where the energy carrier is PE and GHG intensive. Furthermore, implementation might be desirable because of higher thermal and living comfort, better indoor air quality as well as for the sake of humidity and mold prevention.

- A heat pump heating system is an appropriate selection in order to reduce GHG emissions and non-renewably PE use and is especially recommended when low carbon electricity is used (certified or renewably produced on-site). From a long term cost perspective to reduce the energy demand of the building by improving the energy performance of the building envelope prior to the installation of the heat pump is recommended, especially for ground source heat pumps. Thereby heat load and load dependent system costs (length of the borehole and size of the heat pump) can be reduced and the efficiency of the heat pump increased.
  However, the combination of the lower insulation level and larger size of the heat pump heating system may lead to lower yearly costs than the combination of the higher insulation level and smaller size of the heat pump heating system. See the "LCC optimal, GHG and PE oriented" strategy variants on the page 110 – 112. Thus, the heat pump heating system is recommended with the carefully selected insulation level (efficiency level and the building elements to be retrofitted).
  Additionally, district heating system reduces GHG emissions and PE use significantly and is recommended if the energy carrier for heat production is renewable or waste. A wood heating system only reduces GHG emissions and non-renewable primary energy use. The total PE use is only marginally decreased or may even increase compared to an efficient oil or gas heating system. The wood heating system is recommended if the goal of the retrofit strategy is to reduce the GHG emissions.

- Appropriate selection of retrofit measures can result in high GHG emissions mitigation and PE use reduction with the same life cycle costs than a bad selection of measures. (See "investment scrooge" and "LCC optimal GHG and PE oriented" strategies in Figure 58 and Figure 59). Thus, it is recommended to carefully evaluate the strategies with the INSPIRE tool.

- Given decreased prices that reduce costs of PV installations and assuming a net metering regime, PV is recommended due to quite favorable cost effectiveness (as compared to other measures).

- Embodied energy use in the case of building retrofit usually doesn't play the same role as in the case of new building construction. In existing buildings the scope of action to reduce embodied energy use within building retrofit is limited, except in the case of building extensions. The selection of lower embodied energy content in the envelope insulation material reduce only slightly GHG emissions and PE use, but might be considered as an additional criterion, especially in the case of new buildings.

Finally it is recommended to ex-ante assess the effect of different combinations of measures (for instance using the INSPIRE tool).

Recommendations for a strategy focusing on GHG emissions mitigation

In the following the recommendations for strategies with a focus on GHG emissions reduction are presented:

- The wood and heat pump heating system have the highest impact on the GHG emissions mitigation. The other recommended heating system is district heating in case of a low carbon production mix. These two heating systems are also cost effective in terms of the life cycle costs. The wood heating system mitigates effectively GHG emissions as well but is less cost effective.
- The selection of low carbon electricity (renewable electricity or renewably produced on-site) is recommended, especially in case of a heat pump heating system, in order to reduce GHG emissions and additionally, PE use.
- Building envelope insulation measures are recommended if the energy carrier for heating has a relatively high CO_2 content and PE intensity. However, if heat pump, district heating or wood is used, they are hardly cost effective.
- A PV installation is recommended to mitigate GHG emissions, especially, if the used electricity mix has a relatively high CO_2 content. The CH-mix used in the calculations has a slightly higher CO_2 content than the certified electricity mix.
- Building automation is rather recommended to mitigate GHG emissions particularly if heating and electric energy carriers have relatively high CO_2 content.

Recommendations for a strategy focusing on primary energy reduction

In the following the recommendations for strategies with a focus on PE use reduction are presented:

- The heat pump heating system with a certified electricity mix is recommended in order to effectively reduce PE use. If the heat pump heating system is used with the higher PE content electricity mix, the total PE use is increase and not recommended in terms of PE use mitigation. In this case the district heating system is recommended (with Zurich mix or similar). A wood heating system is not recommended selection in terms of total PE use but it is recommended in terms of non-renewable PE use.
- The selection of a certified electricity mix is recommended, especially, if the used pre-existing electricity mix has a relatively high PE intensity (typically caused by nuclear and/or coal).

- A PV installation is recommended to mitigate PE use, especially, if the electricity mix used has a relatively high PE intensity and if on-site use is possible.
- Envelope insulation measures are recommended to reduce PE use. However, the cost effectiveness of the measures depends on the envelope insulation level before retrofitting. Hence, it is less recommended for buildings that are retrofitted or built after the 1990s.

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Annex

5.1 Sensitivity of building period

The sensitivity of building period is investigated. The building period is changed from 1975-1990 to 1947-1975 in order to see how different strategies in Table 26 behave. This change influences to the U-values of the building envelope elements and thus, heating demand is increased. The geometry of the building is maintained. The characteristics of the base case building used in Chapter 3 and new characteristics after changing the building period are indicated in Table 30.

Parameter	Unit	Multifamily house Switzerland	Multifamily house Switzerland
Construction period		1975-1990	1947-1975
Gross heated floor area (GHFA)	m^2	730	730
Façade area (excl. windows)	m^2	552	552
Roof area pitched	m^2	340	340
Area of windows to North	m^2	31.6	31.6
Area of windows to East	m^2	39.5	39.5
Area of windows to South	m^2	47.4	47.4
Area of windows to West	m^2	39.5	39.5
Area of ceiling of cellar	m^2	240	240
Average gross heated floor area per person	m^2	40	40
Typical indoor temperature (for calculations)	°C	20	20
U-value façade	$W/(m^2*K)$	0.5	1.3
U-value roof pitched	$W/(m^2*K)$	0.6	0.85
U-value windows	$W/(m^2*K)$	1.8	2.7
G-value windows		0.7	0.7
U-value ceiling of cellar	$W/(m^2*K)$	0.6	0.9
Energy need for hot water	MJ/ m^2	75	75

Table 30: The characteristics of the base case building from two different construction periods.

The results of the sensitivity analysis are summarized in Figure 60 and Figure 61, and marginal costs and benefits are indicated in Table 31 and Table 32 similarly than in the section 3.7.

To interpret the results it is emphasized to keep in mind that the base case building used in the strategy calculations is now assumed to be from the construction period 1947-1975 instead of 1975-1990. Due to this heating demand of the building and the initial yearly costs are higher than in the case of the construction period 1975-1990. Also it should be noted that GHG emissions and PE use (and to a certain extent also the yearly costs) are higher in the base and reference building for the “investment scrooge” and “technology focus” strategies due to missing basement insulation which was undertaken in the past for the environmental friendly strategies. Additional remark is that the façade measures are extended with the windows in order to get near the same insulation level than in the building with later building period (1975-1990). For example, in the PE oriented strategy the Step 1 is now insulation of façade and new windows. See Table 26.

If compared Figure 58 and Figure 59 to Figure 60 and Figure 61 respectively, it can be seen that the most sensitive measure for the construction period is M1 “Improvements of the thermal protection by insulation of building envelope”. In each strategy, in which the measure M1 is undertaken (see Table 26), the marginal costs are lower or even negative and benefit higher in terms of GHG emissions mitigation and PE efficiency increase. See Table 31 and Table 32.

Additionally, the measures M2 (change of heating system), M3 (a ventilation system with heat recovery) and M6 (building automation) are also sensitive for the construction period of the building because all these mentioned measures influence to heating demand. In terms of GHG emissions and PE use these measures result in higher benefits in each strategy than in case of the other building period. See Table 31 and Table 32.

The measures that have an impact on electricity use (M4, M5, M7) are not sensitive for the construction period.

As a conclusion the measures that influence to heating demand are sensitive for the construction period of the building due to the changing envelope insulation level and heating demand. However, the measures that influences to electricity use are not sensitive for the construction period.

The strategies, that reach the SIA 2024 guide values, are not sensible for the building period. In terms of GHG emissions the strategies “LCC optimal GHG oriented” and “LCC optimal GHG and PE oriented” reach the guide value 6 $kgCO_{2eq}/m^2a$ and in terms of PE use the target 450 MJ/m^2a is reached by the “PE oriented”, “LCC optimal PE oriented” and “LCC optimal GHG and PE oriented” strategies.

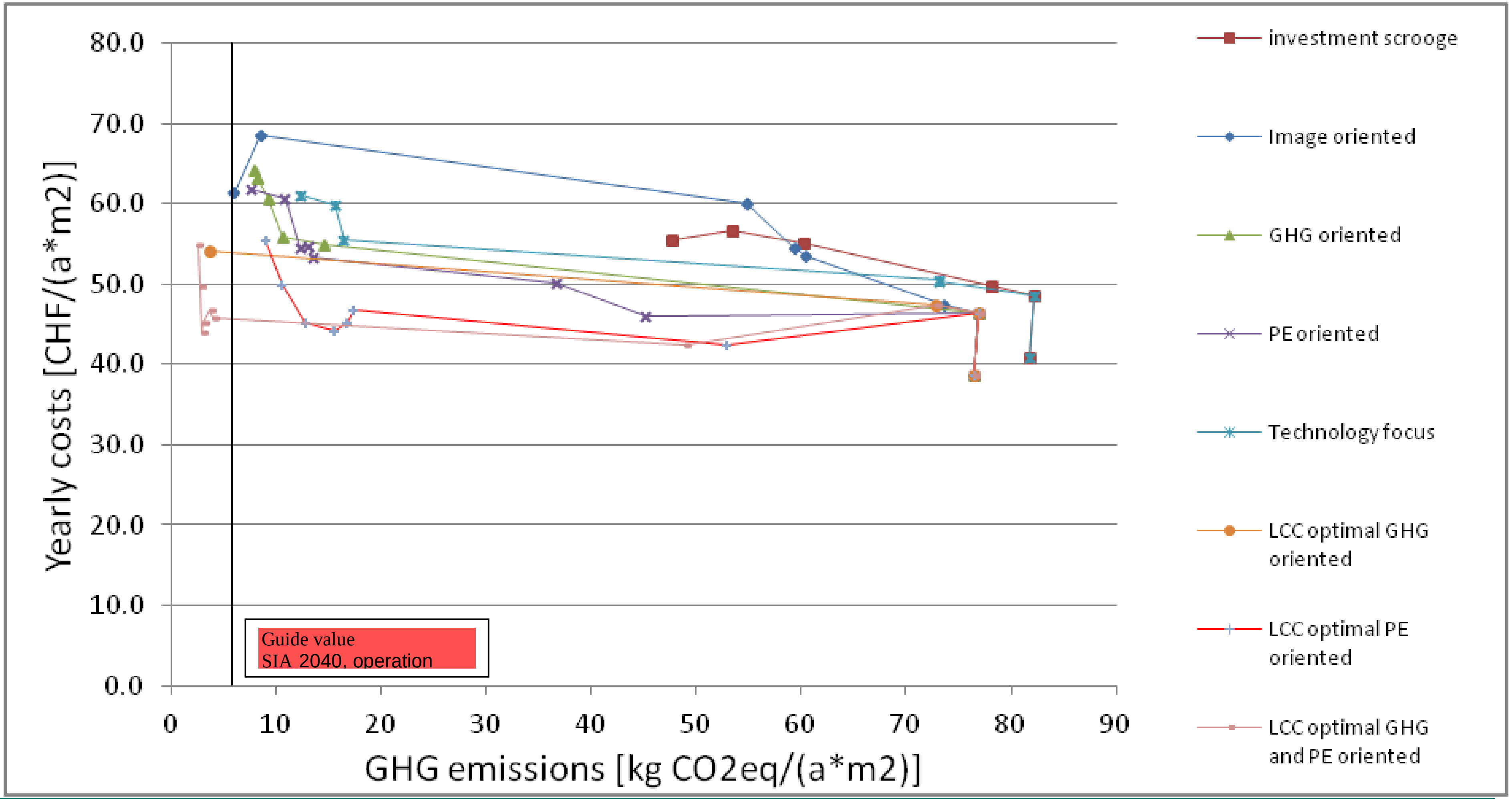

Figure 60: Yearly costs as a function of GHG emissions due to the strategy steps of the each main strategy (applied to the base case building from the construction period 1947-1975).

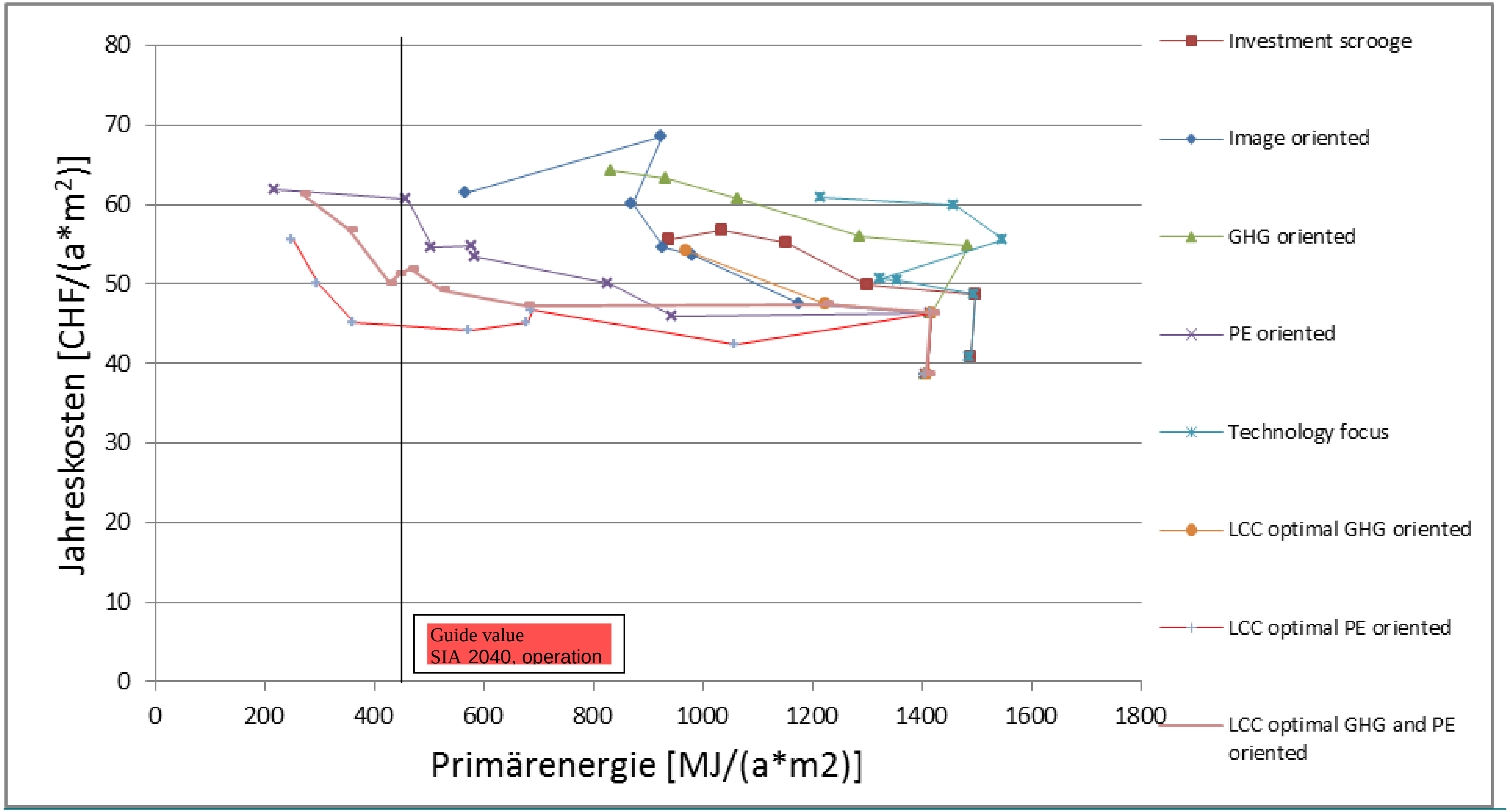

Figure 61: Yearly costs as a function of PE use due to the strategy steps of the each main strategy (applied to the base case building from the construction period 1947-1975)

Measure	Description	Investment scrooge		Image oriented		GHG oriented		PE oriented		Technology focus		LCC optimal GHG oriented		LCC optimal PE oriented		LCC optimal GHG and PE oriented	
		CHF/kg CO_{2eq}	$kgCO_{2eq}$/(m^2a)	CHF/kg CO_{2eq}	$kgCO_{2eq}$/(m^2a)	CHF/kg CO_{2eq}	$kgCO_{2eq}$/(m^2a)	CHF/kg CO_{2eq}	$kgCO_{2eq}$/(m^2a)	CHF/kg CO_{2eq}	$kgCO_{2eq}$/(m^2a)	CHF/kg CO_{2eq}	$kgCO_{2eq}$/(m^2a)	CHF/kg CO_{2eq}	$kgCO_{2eq}$/(m^2a)	CHF/kg CO_{2eq}	$kgCO_{2eq}$/(m^2a)
M 1	Improvements of the thermal protection by insulation of building envelope	-0.22	5.7	0.46 -2.79	13.2 2.5	3.38	1.4	-0.01	32					0.07	33	-0.01	36
M 2	Choice of energy carrier/ Change of heating system	0.30	17.9	0.18	46.3	0.14	62	0.14	23	0.09	56.7	0.10	69	0.07	29	0.06	32
M 3	Implementation of ventilation system with heat recovery functions			1.21	4.5			0.49	8.5	5.05	0.8			2.53	1.8	15.90	0.3
M 4	More efficient electricity services (such as lighting, cooling, appliances)							-0.23	0.8	N.A	-0.02			1.41	0.5	-11.32	0.1
M 5	Choice of energy supply mix (electricity or district heating)	0.29	4	0.91	1.1	0.29	4.0					0.29	4.0			0.29	4.0
M 6	Control and regulation of the energy-related building systems and applications	0.24	6.9			2.4	1.1	4.32	1.4	0.19	9			3.44	1.7	64.45	0.1
M 7	On-site energy production: Implementation of solar thermal panels, PV or wind			0.36	3.3	2.86	0.3	0.36	3.3	0.36	3.3			0.35	2.9	11.7	0.2
M 8	Construction design & material choice with low embodied PE and GHG emissions							3.57	0.4					-0.8	0.9	-1.03	0.6

Table 31: Marginal costs of GHG mitigation (CHF/kgCO_{2eq}) and marginal benefit (kgCO_{2eq}/(m^2a)) of the measures within each strategy applied to the (applied to the base case building from the construction period 1947-1975)

Measure	Description	Investment scrooge		Image oriented		GHG oriented		PE oriented		Technology focus		LCC optimal GHG orient-ed		LCC optimal PE oriented		LCC optimal GHG and PE oriented	
		CHF/ MJ	MJ/ (m^2a)	CHF/ MJ	MJ/ (m^2a)	CHF/ MJ	MJ/ (m^2a)	CHF/ MJ	MJ/ (m^2a)	CHF/ MJ	MJ/ (m^2a)	CHF/ MJ	MJ/ (m^2a)	CHF/ MJ	MJ/ (m^2a)	CHF/ MJ	MJ/ (m^2a)
M 1	Improvements of the thermal protection by insulation of build-ing envelope	-0.013	97	0.03 -0.02	194 355	0.02	225	-0.001	471					0.005	495	- 0.0004	5441
M 2	Choice of energy carrier/ Change in the heating system	0.036	149	N.A.	-53	N.A.	-68	0.014	243	0.021	229	0.009	720	0.006	318	0.005	368
M 3	Implementation of ventilation system with heat recovery func-tions			0.09	58			0.04	117	0.08	56.6			0.09	55	0.13	33
M 4	More efficient electricity services (such as lighting, cooling, appli-ances)							-0.003	72	0.008	31.3			0.008	85	-0.04	28
M 5	Choice of energy supply mix (electricity or district heating)	0.006	195	0.019	53	0.006	195					0.006	195			0.006	195
M 6	Control and regulation of the energy-related building systems and applications	0.014	119			0.02	131	0.13	47	0.01	139.3			0.12	49	0.23	29
M 7	On-site energy production: Im-plementation of solar thermal panels, PV or wind			0.005	241	0.01	98	0.005	241	0.005	240.7			0.005	210	0.03	81
M 8	Construction design and materi-al choice with low embodied PE and GHG emissions							0.21	6					-0.05	14.6	-0.05	12.1

Table 32: The marginal costs of PE efficiency increase (CHF/MJ) and marginal PE benefit (MJ_{PE}/m^2) of the measures within each strategy applied to the (applied to the base case building from the construction period 1947-1975)

5.2 Sensitivity of building envelope insulation and heat pump

A sensitivity of the yearly costs to the measure combination of a heat pump and envelope insulation is investigated. At the moment a heat pump power decreases during the strategy steps if the efficiency of a building envelope increases. However, in practice the heat pump can be installed before deciding to invest to the building envelope efficiency. Due to that the heat pump power is fixed. This approach may increase the yearly costs due to higher investment costs of a larger heat pump. However, the increase of building envelope efficiency may also increase the heat pump efficiency due to the lower temperature requirements of the heating system.

In this sensitivity analysis the environmental heat is not taken into account. However, it does not influence final results of the analysis. Taken into account the environmental heat would only reduce the amount of reduced PE energy in Step 2.

Two heat pump cases are investigated:

- Heat pump power and efficiency are fixed after the investment (Step 2). These parameters do not change even the building envelope efficiency is increased during the Step 5.

- Heat pump power is fixed after the investment (Step 2) but the efficiency is changed depending on the building envelope efficiency.

The sensitivity analysis was conducted, as before, for the base case building from the construction period 1947-1975 and 1975-1990. See Table 30. Two construction periods are selected due to the results of the construction period sensitivity analysis.

As a basis to investigate the measure combination of a heat pump and envelope insulation the strategy variant V1 of the “LCC optimal GHG oriented” strategy is selected. However, the step 5 is extended to include also roof insulation and the step 6 is taken off. The strategy variant V1 of the “LCC optimal GHG oriented” strategy is presented in Table 33.

		The investigated strategy variant of the "LCC optimal GHG oriented" strategy
		V1
Step 1	Certified electricity mix (ESU) 97.78% water, 0.83% wind, 0.73% biomass, 0.66% photovoltaic	X
Step 2	Heat pump geothermal	X
Step 3	PV P_p = 20 kW, 16000 kWh/a, 20% onsite use	X
Step 4	Building automation Heating C → A	X
Step 5	Minergie-P **Roof:** Rockwool, Thickness 20 cm, U-value 0.15 **Façade:** Rockwool, Thickness 19 cm, U-value 0.15 **Windows**: Wood Standard, G-value 0.55, U-value 0.78	X

Table 33: The investigated strategy variant of the "LCC optimal GHG oriented" strategy

The construction period 1975-1990

The construction period 1975-1990 with two heat pump cases is investigated. First both heat pump power and efficiency are fixed during the strategy steps (V1_fixed_HP). The installation of the heat pump (step 2) is done before the envelope efficiency increase (step 5). Due to this the heat pump is relatively large which leads to high investment costs. In the second case heat pump power is fixed but the efficiency is changed depending on the building envelope efficiency (V1_fixed_HP_power).

The results of the sensitivity to the yearly costs are presented in Figure 62 and Figure 63 in which the reference strategy V1, and strategies V1_fixed_HP and V1_fixed_HP_power in which the heat pump power is fixed. The both heat pump cases (V1_fixed_HP and V1_fixed_HP_power) result in the higher yearly costs than the V1 in which the heat pump power and efficiency are adjusted depending on the building envelope efficiency. The adjusted heat pump efficiency in V1_fixed_HP leads only to almost negligible lower yearly costs.

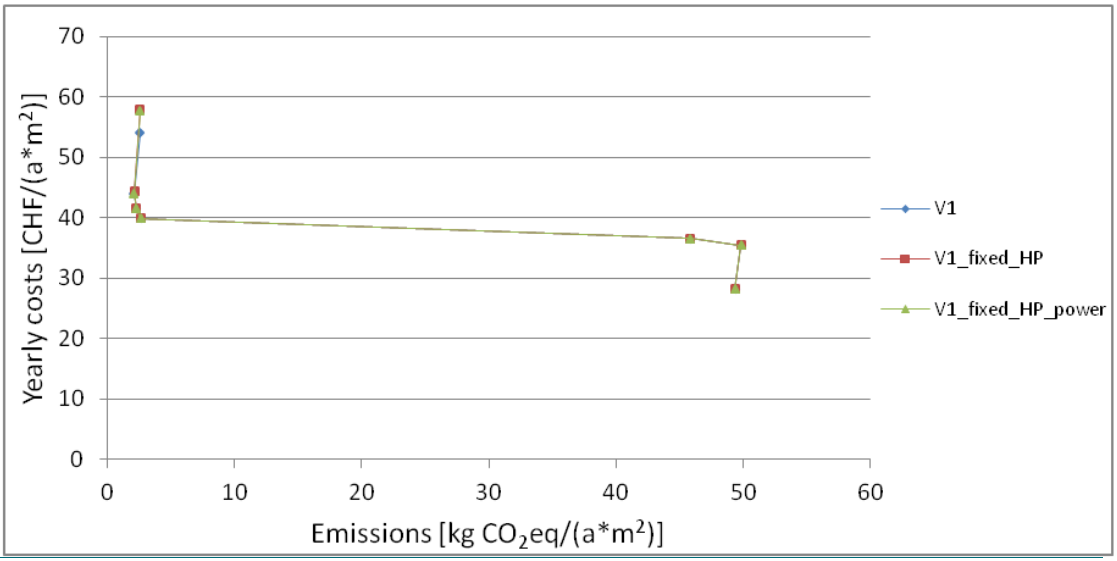

Figure 62: Yearly costs as a function of GHG emissions due to the strategy steps of the strategies (applied to the base case building from the construction period 1975-1990).

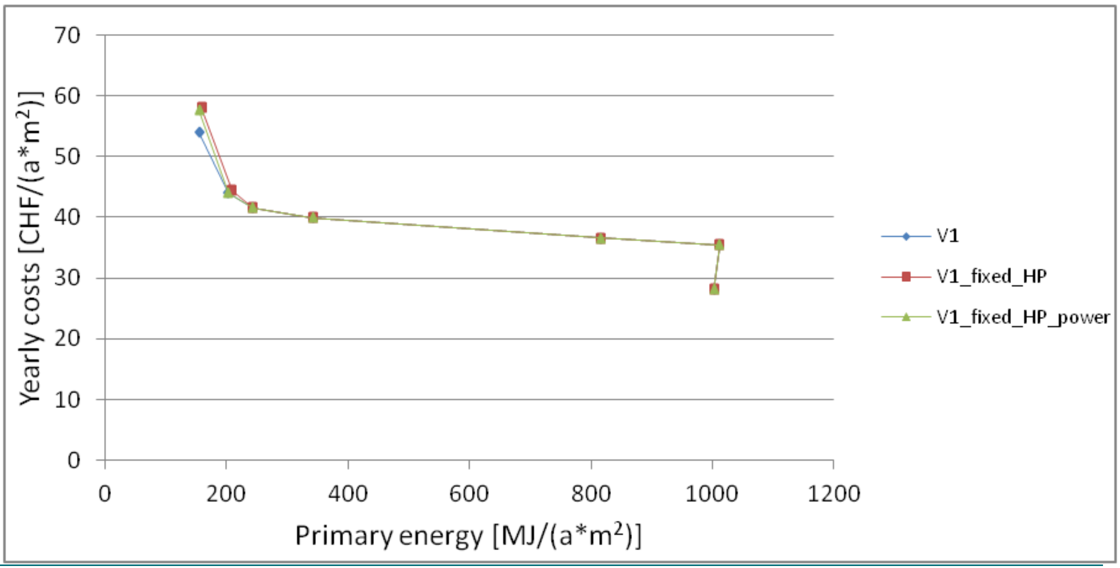

Figure 63: Yearly costs as a function of PE use due to the strategy steps of the strategy (applied to the base case building from the construction period 1975-1990)

The construction period 1947-1975

The construction period 1947-1972 with two heat pump cases is investigated as in 5.2.1. The results of the sensitivity to the yearly costs are presented in Figure 64 and Figure 65. The results of the sensitivity analysis in the section 5.1 show that the insulation measures become more cost effective if the construction period is 1947-1975 instead of 1975-1990. However, if the heat pump power is fixed, the insulation measures are not cost effective. Now, the yearly costs are increased almost 7 CHF/m^2. This result leads to the fact that the investment to the heat pump and building envelope efficiency should be conducted at the same time or in different order in order to have the lowest yearly costs. For example, first implement the insulation and then heat pump installation.

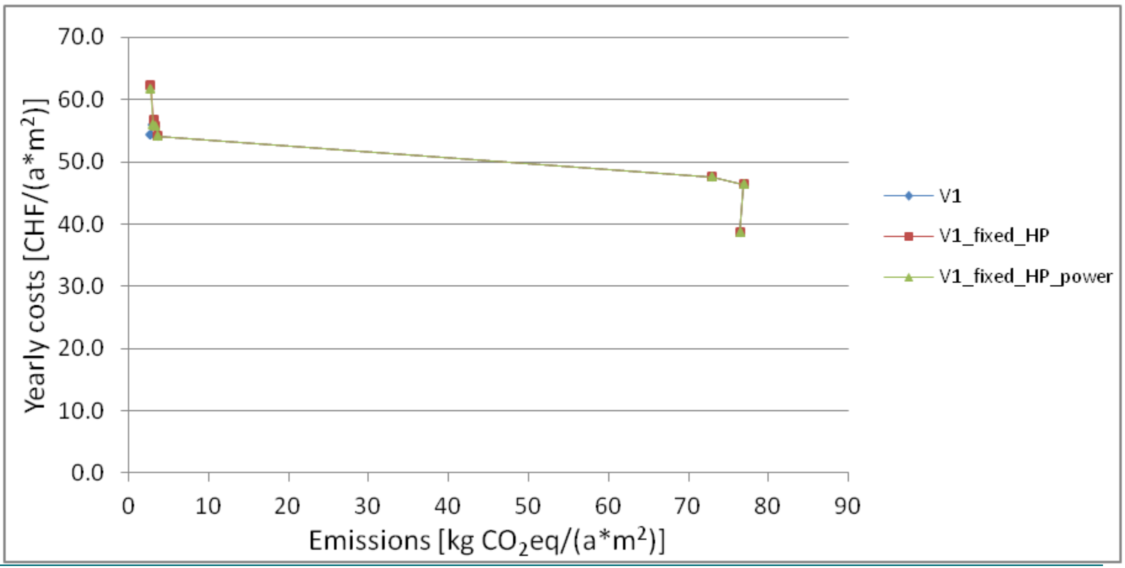

Figure 64: Yearly costs as a function of GHG emissions due to the strategy steps of the strategies (applied to the base case building from the construction period 1947-1975).

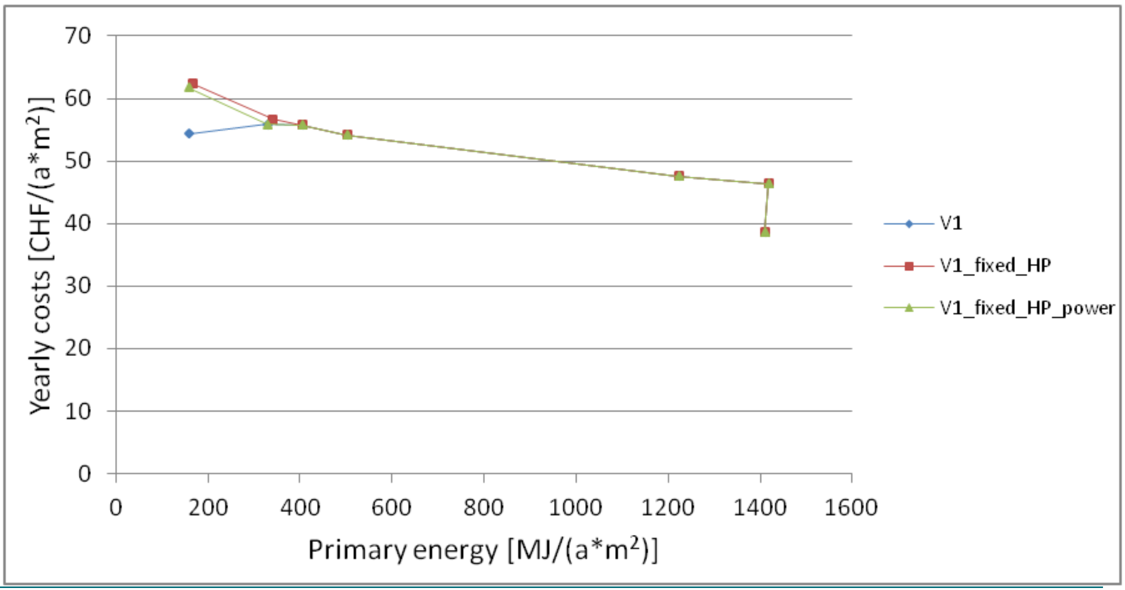

Figure 65: Yearly costs as a function of PE use due to the strategy steps of the strategy (applied to the base case building from the construction period 1947-1975)

5.3 Investment costs of heating system

The investment costs of the heating systems are updated after calculating the strategies in this report. The costs are presented in Figure 66.

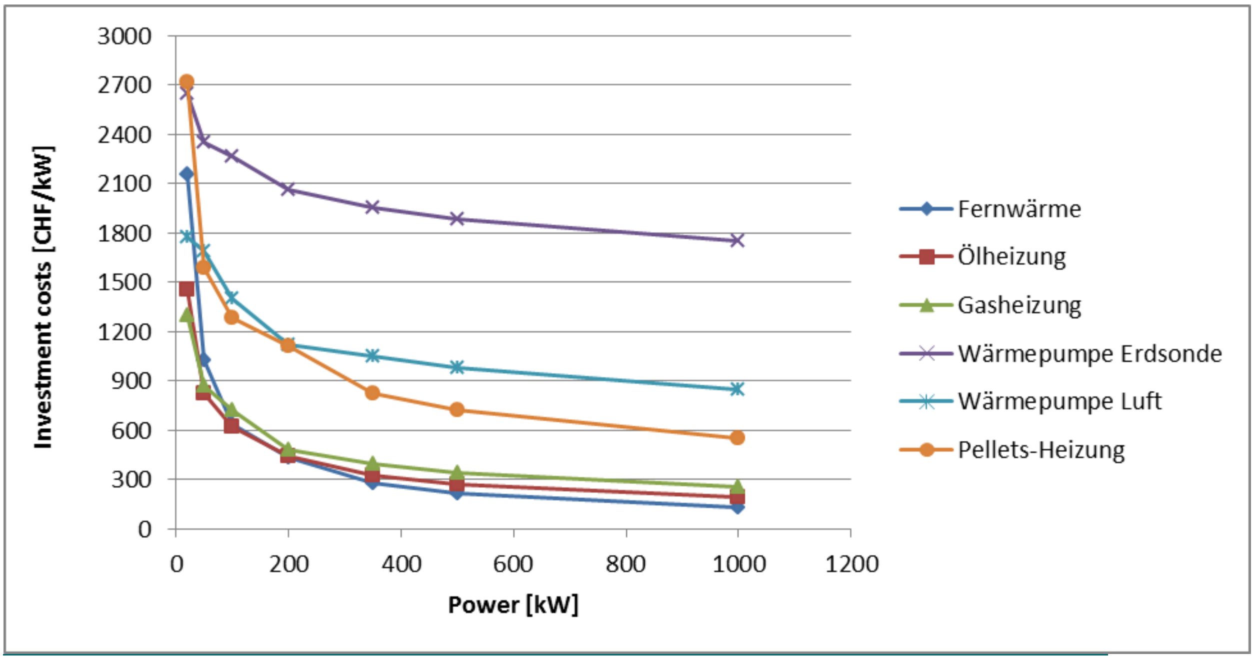

Figure 66: The investment costs of the different heating systems