

# Marginal costs, cost dynamics and co-benefits of energy efficiency investments in the residential buildings sector

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**Note.** This pdf has been updated as per 1 September 2003. Table 1 (page 833) has been replaced by a correct version.

## Keywords

marginal costs, decision behaviour, energy efficiency, co-benefits, residential buildings, cost dynamics, experience curve

## Abstract

Key elements of present investment decision-making regarding energy efficiency of new buildings and the refurbishment of existing buildings are the marginal costs of energy efficiency measures and incomplete knowledge of investors and architects about pricing, co-benefits and new technologies. This paper reports on a recently completed empirical study for the Swiss residential sector. It empirically quantifies the refurbishment practice of building owners, the marginal costs of energy efficiency measures (i.e. additional insulation, improved window systems, ventilation and heating systems and – for new buildings – architectural concepts of low energy building and passive buildings) and first results on co-benefits. The cost-benefit analysis differentiates between widely used windows and insulation standards and newly developed technologies. The latter show large variations in prices due to pioneer market pricing, add-on of learning costs and risk components of the installers.

Impressive techno-economic progress at constant or lower costs has been identified over the last decades. The future costs were obtained based on the empirical basis of the current costs and are important for designing cost efficient and energy effective environmental policies. These future costs show for the first time a cost dynamic of energy efficiency

measures, of which decision makers in politics and administrations are scarcely aware.

Thus, limiting the decisions to costs and energy related benefits is likely to lead to erroneous decisions. Indeed, first results of newly developed adequate methods for their monetisation show that co-benefits such as improved comfort of living, good indoor air quality, better noise protection etc. may amount to the same order of magnitude as the energy-related benefits.

## Introduction and scope

In Switzerland – like in many other countries of the temperate zone – large and mostly untapped energy efficiency<sup>1</sup> potentials lie, amongst others, in decreasing space heating requirements, which make up approx. 50% of the useful energy and approx. two thirds of the final energy demand. Useful energy requirements for space heating of existing buildings could be reduced by approx. one third to fifty percent compared to the present average value for the building stock and improvements by a factor of 5 to 10 can be achieved for new buildings (again compared to the average of the existing building stock), see Ecofys 2002; Avasoo, 1997; Kanton Zürich, 1998; Jakob et al. 2002; Binz et al., 2002; www.minergie.ch, 2000.

In view of the objectives of the Swiss CO<sub>2</sub> law, which consists of reducing fossil fuel associated CO<sub>2</sub> emissions in 2010 by 15% compared to those of 1990, this energy efficiency and CO<sub>2</sub> reduction potential is of great significance concern-

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1. In this paper, energy efficiency measures, energy efficiency investments, energy conservation etc. are used as synonyms.

ing buildings, in particular residential buildings, not only because it is so extensive, but also because of the presumed low cost of tapping these potentials. However, at present many house owners and builders undertaking refurbishments barely take advantage of this potential.

Indeed, building refurbishment with thermal protection was (and still is) often neglected by house owners for several reasons. Only one quarter to one third of the façade refurbishments carried out in the past decade included energetic refurbishment (Jakob et al., 2002). The remainder only received plaster repairs, or rather a new coat of paint. For roofs and windows the share of energetic refurbishments is slightly greater. For windows this is particularly the case because in the last 15 to 25 years window refurbishment mostly meant window replacement and because only noticeably improved windows were available due to great technological advances. Overall there is still a very large potential for lowering energy requirements of the building stock, as the share of the not yet energetically improved construction components is still between 30% and 80%, depending on the component (roof, wall, window, cellar ceiling, etc.). In addition, the building envelope is often not completely refurbished, as the inquiries and surveys carried out on building façade and roofing companies have shown. The energy requirements of refurbished buildings do therefore generally not decrease to the low energy consumption levels of existing new buildings. However, from a construction technology point of view it is perfectly possible to reach this or an even lower level<sup>2</sup>, as the multitude of MINERGIE label and P&D projects carried out in the last few years have shown (see examples in Binz and Schneider, 2000, EMPA 2003).

Commonly given arguments for not fulfilling the complete energy efficiency potential are the energy paradox (Jaffe and Stavins, 1994), (temporary) budget constraints, inadequate tenancy laws (Metron, 1998), insufficient knowledge of cost and benefits etc. Often, investors, house owners or interest groups also refer to the poor economic profitability of energy efficiency measures, while on the other hand emphasis is laid on the extremely low cost level of energetic and environmental improvements. Thus, an up to date, adequate and comprehensive economic assessment of energy efficiency measures with regard to the present and future costs and benefits of these options, as well as the shape of the marginal cost curve, form an important basis of information.

In addition to a differentiated updating of the present costs, the cost development of energy efficiency concerning building envelopes and heating systems is an important basis for long-term decision-making. The future cost development is frequently an issue of new technologies, new materials and building concepts or processes. These partly include considerable learning potentials or serial production potentials, which could, in future, reduce the costs of these new technologies and building concepts. So far these cost

dynamics have rarely been examined for the case of building envelopes.

During the long life time of thermal protection investments in buildings an increasing energy price level must be reckoned with in the coming decades due to an expected production maximum of mineral oil. This should also be considered in the assessment of the benefits of thermal protection investments.

The assessment of such investments in residential buildings is not only concerned with an energy benefit, but also other accompanying benefits. These consist of ancillary benefits and co-benefits and include, for example, increased living comfort and operating ease, noise protection, additional safety, lower occurrences of respiratory illnesses, and improved leasing potential or betterment. These ancillary benefits and co-benefits are usually neither mentioned nor quantified. They are monetised in only few cases. However, they may present further elements to the real estate economy, as well as to the tenants and builders, which may facilitate an appropriate and comprehensive economic assessment. Finally and from an economical point of view, there remains the aspect of avoiding external costs by reducing emissions.

This paper reports on a recently completed empirical study for the Swiss residential sector (Jakob et al., 2002), the main objective of which was to improve the knowledge of the marginal costs of enhanced energy efficiency investments, i.e. to place it on a differentiated new empirical basis, following a non-trivial approach (e.g. not only considering the insulation material as a function of the insulation thickness, but also additional cost components, such as mechanical structures, labour costs etc.). The paper is organised as follows: First the methodological approaches of the empirical inquiries and the calculation of the marginal costs of the direct costs are outlined, and the energetic benefits described. In a second step it is explained why this business economic valuation approach alone would be insufficient if decisions on energy efficiency investments were to be based on it.

### Costing methodology of the marginal cost concept

How much more does a greater insulation thickness or a more energy efficient window cost and how much energy efficiency gain and what further cost reductions can be reached by it? What is the cost of conserved energy? How do these costs compare to the conserved costs of energy (heat) generation? To answer these questions we define the marginal cost of energy efficiency ( $mc_{EE}$ , eq.1) and the average cost of energy efficiency ( $ac_{EE}$ , eq.2). The two approaches can be characterised as follows:

- Marginal cost approach, defined as the first derivative of the cost as a function energy conservation or for practical

2. Most construction elements (like walls, roofs, windows, cellar ceilings etc) of existing buildings can be energetically refurbished to a similar thermal protection quality as today's new buildings, i.e. insulation of 10 to 14 cm is added or existing windows are replaced with such of glazing-U-values of for instance 1.1 W/m<sup>2</sup>K. Most heat loss of the thermal bridges can be removed at similar specific costs as area elements and only few thermal bridges might only be refurbished at high specific cost, but the energy loss of the latter could be compensated by applying more insulation to area elements. Indeed, an insulation thickness 20 cm or even more doesn't cause any technical difficulty and the architectural challenge can be met in most of the cases. If the whole building envelop is refurbished specific space heating demand can be reduced to less than 150 MJ/m<sup>2</sup>a and to less than 150 MJ/m<sup>2</sup>a if additionally care is paid to air renewal heat loss.

reasons additional costs and benefits compared to the previously defined (discrete) efficiency step levels. The marginal cost approach is applicable for the macro-economic consideration and for energy economy models for the purpose of rational arrangement and restriction of support programs, energy or CO<sub>2</sub>-tax, etc. For example the additional costs of an insulation of 16 cm are compared to 12 cm, 20 cm to 16 cm, 24 cm to 20 cm etc. are contrasted to the associated efficiency gain (reduced transmission loss).

- **Average cost approach**, defined as additional costs and benefits compared to the reference case, see below: suitable and in practice used for comparison of investment variants compared to a reference investment, in particular for house owners and the real estate economy (investors and administrations). All the different efficiency levels are hereby compared to the same reference, e.g. the insulation thickness 16 cm with 12 cm, 20 cm likewise with 12 cm, 30 cm likewise with 12 cm. Due to its ‘marginal’ character as referred to a reference project the average cost approach can also be termed as ‘project marginal cost’

$$\begin{aligned}
 mc_{EE} &= \frac{dCapCost}{dD_{Energy}} \cong \frac{\Delta CapCost}{\Delta D_{Energy}} = \\
 &= \frac{CapCost_n - CapCost_{n-1}}{D_{Energy,n} - D_{Energy,n-1}} = \\
 &= \frac{a_n \cdot IvcCost - a_{n-1} \cdot IvcCost_{n-1}}{D_{Energy,n} - D_{Energy,n-1}}
 \end{aligned} \tag{1}$$

$$ac_{EE} = \frac{a_n \cdot IvcCost_n - a_0 \cdot IvcCost_0}{D_{Energy,n} - D_{Energy,0}} \tag{2}$$

where *CapCost* and *IvcCost* denote the capital cost and the investment cost of the energy efficiency investment considered, *a* the annuity factor and *D<sub>Energy</sub>* the energy demand of the buildings or of the construction element considered. The indices *n*, *n-1* and *0* denote the energy demand levels considered, i.e. the various points on the marginal cost curve. The *0* indices refers to the reference cases which are defined as follows:

- **New buildings**: the present energetic regulations with regard to space heating requirement of buildings (SIA 380/1, corresponding to EU-Standard EN832), or rather the actually realised energetic quality of the new building which was empirically surveyed by Brühlmann et al. (2001).
- **Maintenance of existing buildings**: maintenance activities on the building envelop, such as plaster renewal,

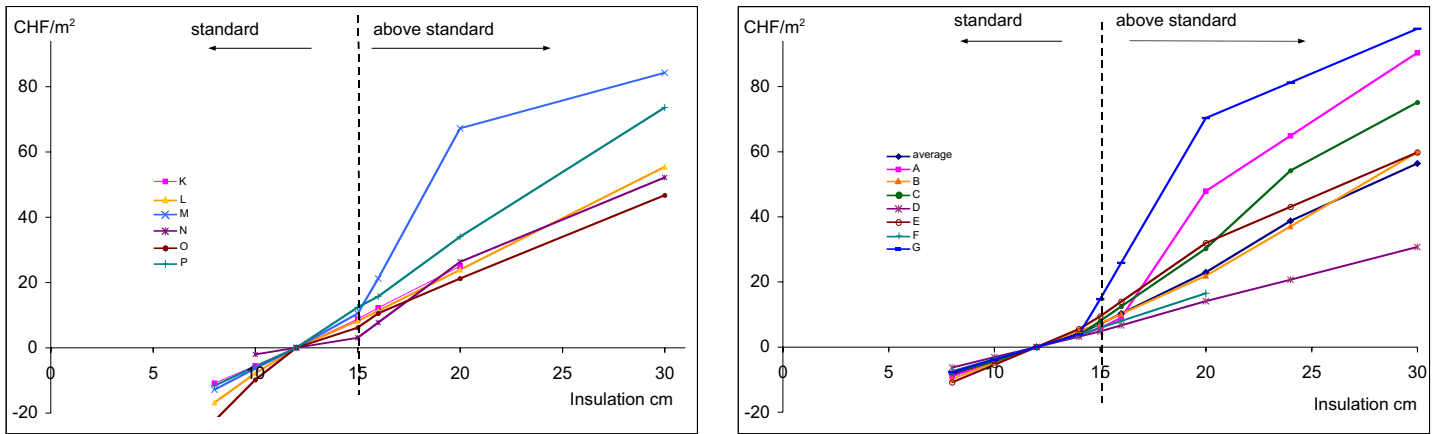
painting of façade, roof maintenance, tile replacing etc., could be used as an occasion to carry out efficiency measures. In these cases and with regard to energy the reference case corresponds more or less with the energetic quality of the original buildings (since the mentioned maintenance activities do not improve the energetic quality of the building envelope), whereas cost reference is defined by the maintenance costs.

- **Energetic refurbishment of existing buildings**: each year a fraction of the building stock is not only maintained, but also energetically renewed. These energetic refurbishments are the reference case for so called enhanced energy efficiency measures and the *mc* are of the type ‘What are the specific costs of conserved energy if, for instance, 20 cm of insulation is added instead of only 12 cm’. Both costs and energy relevant technical parameters of this reference case were empirically determined, e.g.:  
 Façade insulation: 12 cm  
 Roof insulations: about 14 cm insulation thickness  
 Windows:  
 U-value<sub>glazing</sub> = 1.1 W/m<sup>2</sup>K;  
 U-value<sub>wood frame</sub> = 1.4 W/m<sup>2</sup>K;  
 U-value<sub>synthetic-frame</sub> = 1.6 W/m<sup>2</sup>K.

The following methodological approach was taken to empirically determine the *mc* of energy efficiency of the Swiss residential building sector.

- Inquiries concerning cost structure of façade and roof insulations with regard to insulation thickness, prices of glass and windows, as well as ventilation systems with regard to their ventilation efficiency were made directly of companies. Particular interpretation problems of price statements of new technologies are discussed below.
- For individual components the energetic effect, i.e. the energy efficiency gain (=reduction of space heating requirements) was calculated using the U-value (where linear effects also become increasingly important when assessing highly efficient energy measures), while for the building as a whole it was calculated using a physics of building model (complying with SIA 380/1).
- The annual cost differences were calculated using the reference cases (see above) and the annuity method. The latter makes considerations for the specific lifetime of the energy measures and for interest rates.
- Individual investment measures were summarised into a cluster of measures, or rather investment packages, based on the specific marginal costs and/or physics of building aspects, both on the level of individual buildings and of the building stock as a whole.

As most energy efficiency measures are matters of constructional investments with low maintenance cost share the share of capital costs mostly lies at around 100% (with the exception of ventilation systems). Thus, the annual, or rather marginal costs are accordingly sensitive to the assumption of the real interest rate. From a macro-economic point of view a real interest rate of 3% to 3.5% is regarded as appropriate and is used for the marginal cost approach. This interest rate might be suitable also for private building owners, but large institutional investors might apply higher interest



**Figure 1.** Additional investment costs for wall insulations for ventilated façade (left) and a compact façade (right) compared to the reference insulation thickness of 12 cm as a function of insulation thickness. Empirical data from different Swiss building companies (tagged A-P).

rates. This is also the reason why the (project orientated) costs were calculated using a real interest rate of 5.5%.

Finally, the marginal cost or average cost of energy efficiency can be compared to the marginal cost of space heating generation and distribution. The latter consists of cost savings associated with smaller heating systems, but mainly of the reduced cost concerning energy purchase and is thus highly dependent on current and future energy prices. There are two good reasons to believe that energy prices will increase during the long life time of construction-orientated energy efficiency investments (Jochem and Jakob, 2002): (i) a rapid industrialisation and motorization of China, India and South America in the coming few decades, resulting in a large increase in the world-wide energy use and coinciding with a decrease in production possibilities for oil and natural gas in the non-OPEC states. (ii) The Swiss CO<sub>2</sub>-law and the obligations of most industrial states according to the Kyoto protocol are possibly only the beginning of political reactions to climate change. Even a moderate CO<sub>2</sub>-tax of 100 CHF/t CO<sub>2</sub> (67 Euro/t CO<sub>2</sub>) or an emissions certificate of 70 \$/t CO<sub>2</sub> would cause roughly a doubling of the present oil and natural gas retail prices and would cause a prominent increase of heating costs (0.020 Euro/kWh for oil heating systems and 0.015 Euro/kWh for natural gas heating systems, assuming 0.9 efficiency).

In addition to the costs and benefit calculations described above, other elements must also be taken into consideration, if an integrated economic valuation is to be achieved: (i) the market environment of the cost surveys, (ii) technological progress and its induced cost dynamics, (iii) the economic valuation of the saved energy and the ancillary benefits of the investments and (iv) from a macro-economic point of view avoided external costs.

### Marginal Costs of Energy Efficiency – The Building Owners' Perspective

For façade companies working on compact façades and ventilated façades and for roofing companies costs were calculated with regard to insulation thickness (see Figure 1 as example). The range of the currently common insulation

thickness (10 to 12 cm) of up to 30 to 35 cm was covered and both the total costs and the cost structure were investigated. This showed that costs for insulation materials caused only around one third to one half of the additional costs. The remainder of the additional costs were associated with constructions, fixation material (e.g. specialised plugs and screws, substructures), higher labour costs (more time consuming handling,) and partly additional costs for scaffolding (consoles).

Contrary to expectations the differences in cost curves between new buildings and refurbishments are small. Also the existing wall constructions have only a low influence on the investment costs. The costs for ventilated façades increase less steeply than for compact façades, as for the latter additional mechanical fixing becomes necessary from a certain insulation thickness onwards, while this fortification already exists for ventilated façades. If the construction details and connections between adjacent construction components are examined more closely, the insulation of the embrasure or the roof edge may well cause additional costs during refurbishment, however, the additional energetic effect results in marginal costs of saved energy, which are rarely higher than for surface elements. Coordinated planning of the refurbishments is therefore worthwhile and recommended, even if the refurbishments occur at staggered intervals. Attention should be paid to the physics of buildings principles. If, for example, only the windows were replaced, the building could subsequently be too airtight, which would cause dampness problems on insufficiently insulated walls.

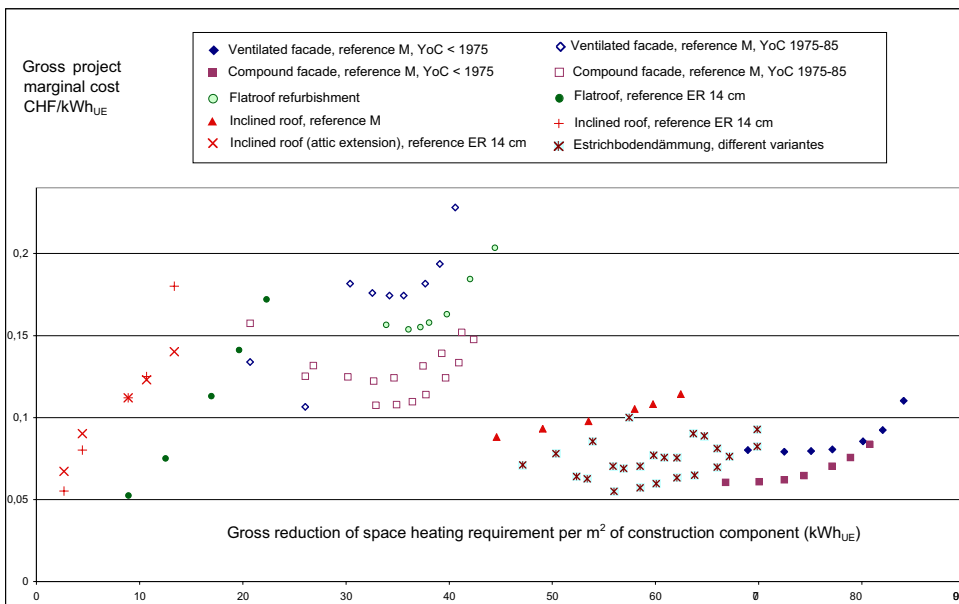
### Economic interpretation of the surveyed cost data

The analyses also show that the cost curve for the currently common insulation thicknesses (8 cm up to approx. 16 cm) is about the same for all companies, which is in contrast to very large variations for greater insulation thicknesses (see Figure 1). When interpreting the cost estimates of enhanced energy-efficiency investments, it must be taken into account, that the appropriate market has only just started developing. The installing companies (or at least part of them) have no or only little experience of the technological aspects where the cost calculations are concerned. The var-

**Table 1. Investments of façade insulations for refurbishments and average cost of energy efficiency (mean value and best practice, real interest rate 3.5%) compared to the reference cases 'maintenance' or 'energetic refurbishment'.**

Insulation thickness (cm)	U-value (W/m <sup>2</sup> K)	Investment costs (CHF/m <sup>2</sup> )		Gross average costs (CHF/kWh <sub>UE</sub> )		
		Mean	Best practice	Compared to Ref. ER		Compared to Ref. M
				Mean	Best practice	Mean
0 (Ref. M)	0.85 - 1.1	35	35	N/A	N/A	-
12 (Ref. ER)	0.28	117	112	-	-	0.061
16	0.23	127	119	0.12	0.08	0.065
20	0.20	140	133	0.17	0.10	0.070
30	0.15	174	143	0.25	0.13	0.084

Ref. M = Reference maintenance (plaster repairs, façade coating)  
 Ref. ER= Reference energetic refurbishment (12 cm external insulation)  
 N/A = non-applicable



**Figure 2. Summarising illustration of gross marginal costs (average costs) for refurbishments (reference cases ER, M) and new buildings.**

iation in costs of such further-reaching measures is accordingly large. Moreover the cost estimates may often represent learning costs or surcharges accounting for the “fear factor”, or the providers assume that the energy aware client thinks of himself as pioneer and therefore accepts higher prices (pioneer market surcharges). Methodologically these facts are taken into account by considering the best practice value in addition to the mean value, and by excluding those values identified as outliers when calculating the mean value.

The mentioned variation has a large influence on the marginal costs (see Table 1). The marginal costs of the company with the lowest price increase (best practice) are nearly half as low as the mean value and are therefore considerably closer to the economic viability, particularly for great insulation thicknesses. From an energy and climate policy point of view it is therefore particularly effective to induce techno-economic progress through market simulation. Given suitable expansion, learning and experience potentials can be activated and pioneer market surcharges can be avoided through greater competition, in order to adapt the costs, or rather the prices of all companies to best practice.

For the reference case ER of a necessary or planned insulation by today’s standard (12 cm energetic refurbishment)

it is apparent from Figure 2 that the average cost curve is approx. the same for most opaque, i.e. non-transparent, construction components, which means that at certain (project) marginal costs the efficiency gain per m<sup>2</sup> is approx. the same. The one exception is flat roofs, where the marginal costs are clearly lower.

For the reference case M (maintenance) the project marginal costs are understandably considerably lower compared to the reference case ER, as the efficiency gain per m<sup>2</sup> of refurbished façade is considerably higher (e.g. 70 kWh<sub>UE</sub>/m<sup>2</sup> for 12 cm compared to 0 cm and 80 kWh<sub>UE</sub>/m<sup>2</sup> for 20 cm compared to 0 cm, while it is only between 7 and 9 kWh<sub>UE</sub>/m<sup>2</sup> from 12 cm to 20 cm).

**Windows and window frames**

In the past energetic improvements of windows have been achieved particularly due to technological progress in the area of glazing. But improved coating, different gas fillings and triple instead of double-glazing can lower the currently reached standard of 1.1 W/m<sup>2</sup> K even further. The additional costs for this are similar for both wood and synthetic windows. There are, however, big differences between small and large windows (see Figure 3). Large windows not only have lower energetic and attractive starting values, which

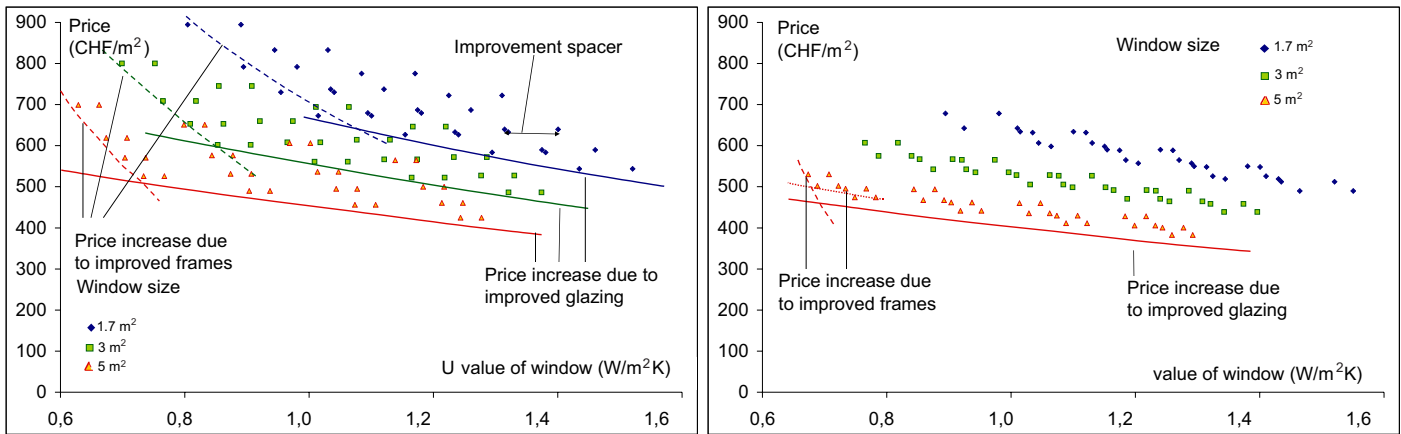


Figure 3. Investment costs for wood windows (left Figure) and synthetic windows (right Figure) for different window sizes in relation to the U-value of the window as a whole.

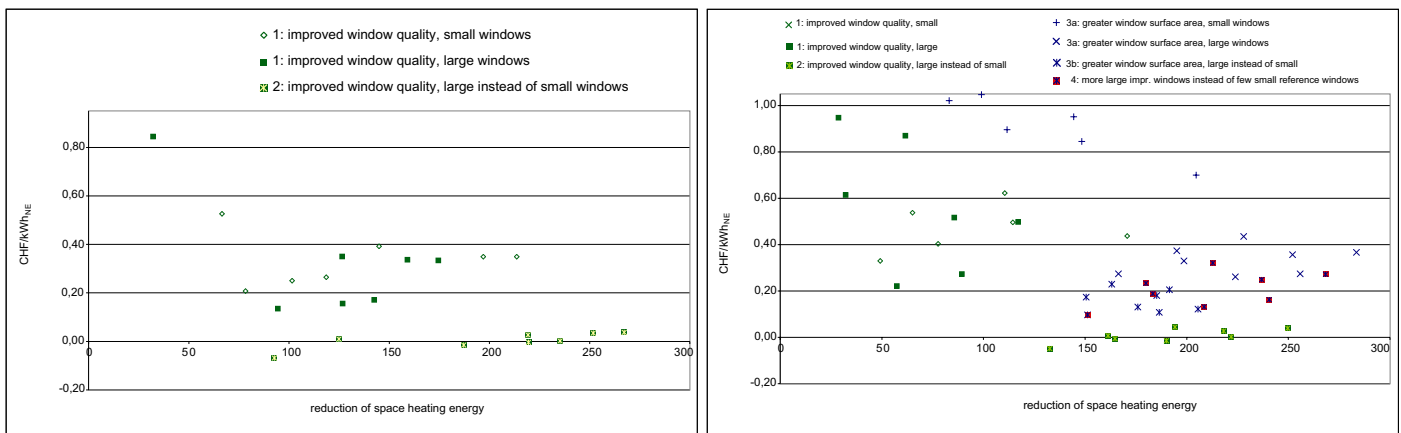


Figure 4. Summarising illustration of the gross marginal costs (average costs) of windows for different cases and orientation (north: left Figure, south: right Figure), real interest rate 3.5%, 30 years lifetime.

are due to the geometric conditions and the fact that the glass has lower U-values than the frame, but also the price increase curve for more energy efficient windows is flatter. A large highly efficient window meeting the German passive house standard can be purchased at comparable specific cost (CHF/m<sup>2</sup>) as a small standard window. The architectural element of designing larger windows is therefore particularly economically attractive in the case of new buildings.

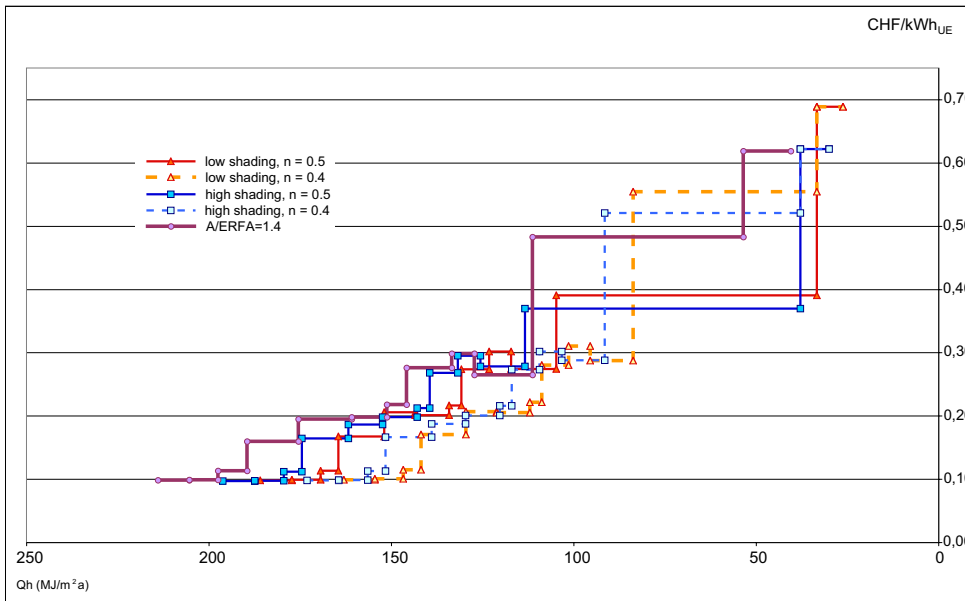
In the last few years attempts have also been made to improve window frames. For synthetic windows this development is further advanced than for wood or wood-metal windows. This is expressed by a wide market supply in the area of frame quality and is also apparent from Figure 3. The price increase of frame improvements is considerably greater for wood windows than for synthetic windows. However, the increasing demand for well-insulated windows due to the 'MINERGIE' label has also induced a supply market for wood windows, which reach all the way to the strict demands of the German passive house standard.

Regarding energy efficiency windows have to be assessed differently to non-transparent construction elements, as for the former the energy balance does not only depend on the reduction of transmission losses, but also the solar gain of the different window and glass types. This implies that for

a certain U-value very different marginal costs can be obtained depending on the orientation, shading, the g-value, window geometry and the ratio of solar heat gain to transmission and air renewal losses in the building. Values for the windows in Figure 4 serve to illustrate this. For south-orientated windows, but also for slightly shaded east- and west-orientated windows the energy flow is positive throughout the entire heating period. Here the windows act as solar collectors and gain solar heat, which has a mitigating effect on space heat demand. Not only low U-values are important for the choice of glass quality, but also the highest possible g-values (total energy transmission efficiency  $\geq 50\%$  of the solar radiation, as otherwise U-value improvements are compensated by lower solar gains).

**The building as a whole**

For the step from individual construction components to the building as a whole it must be considered that the respective costs and the energetic benefits of the different investment areas can partly influence each other. For this reason the cost-benefit relation may be shifted from an isolated consideration to a consideration of the level of the building as a whole. On an energetic level, for example, the useable share of 'free' heat (solar heat gains plus heat from



**Figure 5.** Gross marginal costs for multiple family houses (without consideration of cost reduction on the part of the heat production and distribution) for different starting conditions of shading and of air exchange. Source: calculations CEPE.

people and electrical appliances) deteriorates slightly with increasing insulation or increased solar gain and thus, the energy efficiency gained through insulation decreases and the specific marginal costs increase. There are also interactions on the cost level: the costs for heat production and distribution can be reduced with an increasingly lower space heating demand.

For the existing building stock the surface area ratios or the orientation of a building are given (and can only be altered to a limited extent) and the potential for energy efficiency improvements can accordingly be derived from the individual construction components. However, for new buildings there is a certain scope to influence the energy requirements of a building by using architectural concepts. Such aspects may, for example, involve the avoidance of shading and the use of large windows. When constructing new buildings there is further leeway concerning the cover of the remaining heat requirements, because there is greater freedom of choice for housing technology than for the building stock, where there are additional boundary conditions (e.g. limited space, existing space heat distribution, which would for instance cause low efficiency for heat pumps).

The examination of different concepts for new buildings and different starting positions has shown that the marginal cost curve takes a relatively similar course (see Figure 5). This is explained by the similar marginal cost curve of the individual construction components and the individual measures. There are, however, differences in their appearances; if, for instance, the specific space heating demand ( $MJ/m^2 a_{ERFA}$ ) is already low because of a favourable ratio ‘envelope area’ to ERFA (energy reference floor area), the energy demand can be reduced to a smaller extent and thus, the marginal cost curve appears steeper. In other words: For a given mc less energy can be conserved. In some cases the merit order of the efficiency measures to be taken may also change, if these are to be taken strictly according to the increasing marginal costs. It is, however, more essential that

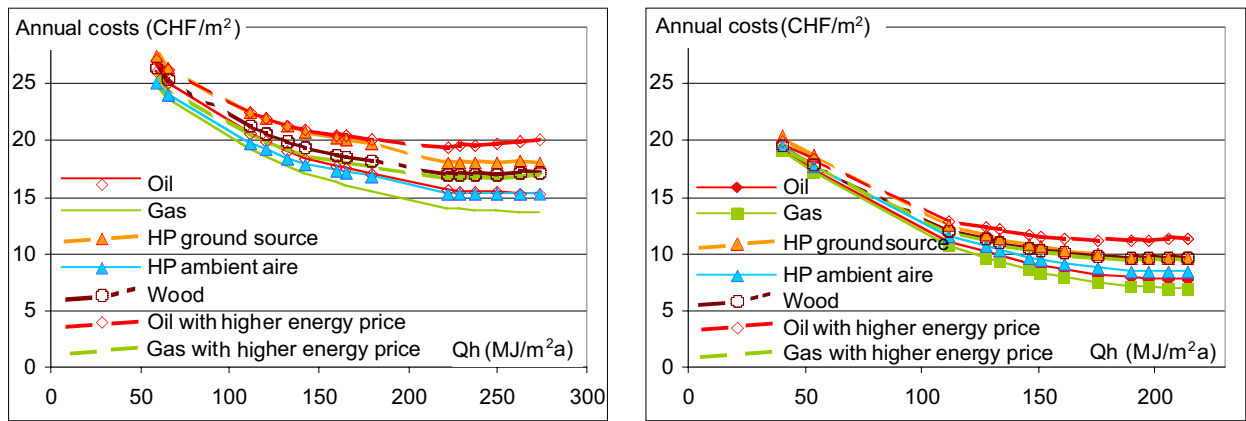
successive measures are taken for all construction components, as opposed to applying selective but high measures to only some of the components.

In the form displayed below (Figure 5) the gross marginal costs enable a comparison amongst the individual investment options, as well as a comparison of different concepts for new construction, but do not enable a final assessment of the economy with the inclusion of heat availability. The calculation of the system size takes place via the performance requirement, while this, in turn, is calculated in a differentiated manner based on the actually considered building concepts. The performance requirement usually decreases under-proportionally to the reduction of the annual heating energy demand, because the coldest day in the absence of solar gains is authoritative to the dimensioning of performance, while the heating energy requirements can be reduced by solar gains. With the possible use of small systems associated obtainable cost reductions are rather low for oil, gas and wood heating. For heat pumps – in particular for the ground source heat pump – investment costs are strikingly reduced (see Figure 6).

At the current costs the additional costs for thermal protection investments cannot be entirely compensated for any system type, even if the hydraulic heat distribution of a well built passive house is not included.

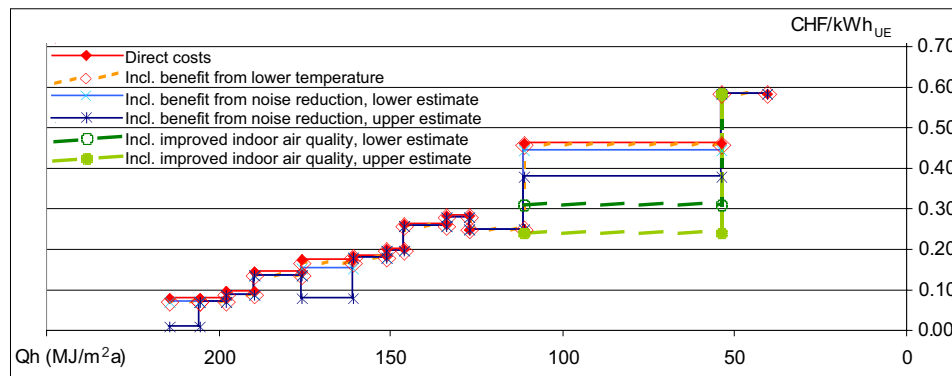
The costs and benefits can also be shown as annual costs with regard to space heating requirements  $Q_h$ , measured in  $MJ/m^2 a$  (see for example Figure 6). This illustration method facilitates a comparison with other cost components of the housing economy, in particular with rent prices.

The calculated total annual (net) costs show – without consideration of ancillary benefits – an initially very flat curve in or below the area of current construction methods (e.g. between 250 and 200  $MJ/m^2 a$ ) (see Figure 6). In the illustrated example an improvement of the specific space heat demand  $Q_h$  of around 40  $MJ/m^2 a$  to 60  $MJ/m^2 a$  (or by approx. one quarter) can be achieved without great addi-



**Figure 6.** Annual costs (with consideration of cost reduction on the part of heat production and distribution) for different system types for single family houses (left Figure) and for multiple family houses (right Figure). Higher energy prices for oil or gas heating: surcharges in the area of 210 CHF/t CO<sub>2</sub>.

Source: calculations CEPE.



**Figure 7.** Marginal cost curve for insulation investments with consideration of selected co-benefits (greater comfort, sound protection, better room air quality due to ventilation systems), case study with oil heating.

Source: calculations CEPE.

tional costs, even when the improbable assumption is made that the average energy price throughout the entire life time is only 0.055 CHF/kWh (approx. 55 CHF/100 lit.). Space heat demands can be reduced by a total of over 100 MJ/m<sup>2</sup>a at net costs of 2 CHF/m<sup>2</sup> to 3 CHF/m<sup>2</sup>, which would mean 20 to 30 CHF of additional costs per month for a flat of 120 m<sup>2</sup>. If an energy price increase in the area of CO<sub>2</sub>-tax is estimated at 210 CHF/t CO<sub>2</sub>, the cost curve becomes even flatter and the economic optimum is moved further to the left to a lower specific energy requirement.

The values in Figure 6 were not based on best practice costs (in connection with this also note the variation in additional costs in Figure 2 or Table 1); in future the cost increase could very possibly be more moderate than illustrated here due to growing learning and economy of scale effects. Also not considered are the non-energetic benefits, which can often be observed for further reaching energy efficiency measures (see below). In this respect the above described business economic net costs are incomplete and can lead to misjudgements where thermal protection and energy efficiency investments are concerned.

In contrast to the annual costs curve which is very flat around the economic optimum (Figure 6, see also Hinz and Feldmann, 2001) the investment costs (e.g. Figure 1) begin to increase immediately after the reference point, if only

marginally. Decisions based only on the investment costs will therefore not result in an energetically and economically optimal construction method. As trivial and as not particularly new as this finding is, it is often not given much attention in reality. In many cases this is due to the investor/user dilemma and tenancy legislation, which is insufficiently aware of these connections.

### Ancillary benefits (co-benefits) of thermal protection investments

Beside of the above described direct and indirect economic effects of energy efficiency measures a comprehensive economic assessment has to include ancillary benefits and co-benefits. In the following, three examples are used to illustrate how the inclusion of such benefits into the business economic assessment can reduce the energetically limited marginal costs (see Figure 7):

- For the quantification of the increase in living comfort empirical investigations on the cosiness were used which were based on differences between wall temperature and air temperature, as well as current conditions in the living space. It was found already years ago (Fanger, 1970 and others) that a reduction of the temperature differ-

ence between the wall of a room and its average air temperature by around 5°C enables a decrease in the room temperature by 1°C without affecting the cosiness level. The consideration of this effect, however, only leads to relatively small ancillary benefits of at best a few cents of CHF per kWh of heating energy.

- Replacement of old double-glazing windows, the installation of double or triple-glazing with asymmetrical glass construction and special glass types, the renewal of roller blind casings as well as (heavy) insulation material made from mineral substances, all help to reduce the transmission of noise energy into the interior of residential buildings. A quantification of the noise reduction can be obtained by estimating the reduction of the noise-associated costs. These noise costs were empirically observed, amongst others, as rent losses as a function of noise pollution and have been given as 0.6% to 0.9% per each additional dB by different studies (Ecoplan, 2000). As a rough estimation we estimate that these economic losses are reduced by fifty percent if a new window replaces an old window without rubber seal. Indeed old windows reduce the level of external noise in the interior of the building by 23 dB, whereas new ones achieve 33 to 35 dB and 38 to 40 dB are possible if (asymmetric) triple glazing is applied. Hence triple glazing offers further energy efficiency potential.
- The by far greater noise reduction effect can be expected from the area of windows and/or blinds and shutters. Its benefit is roughly estimated at about 50% of the above-mentioned specific costs, if a ventilation system is in operation simultaneously. But also insulation measures using mineral materials in roofs are of relevant significance (in particular against air-traffic noise or traffic noise transmitted over large distances). The selected examples show that for windows and roofs sound protection can significantly influence the profitability of the heat protection measures (Figure 7). Converted into benefits per kWh of usable energy the inclusion of ancillary benefits through noise reduction results in values between 0.06 and 0.08 CHF/kWh, i.e. for these examples they lie within current heat prices.
- The use of ventilation systems has a similarly large influence on the improvement of room air quality (see Figure 7). On the one hand either a better air quality in flats of residential buildings located in strongly affected areas (e.g. near busy roads) are reached by either a reduced air exchange rate for windows and doors replacements or by filtering the outside air through ventilation systems and/or by drawing in air from the part of the building turned away from the road. The opposite case is a too low air exchange rate in well insulated residential buildings which have a too damp interior climate (e.g. due to rising damp) or which have a relatively high pollutant concentration caused by the inhabitants (excessive smoking) or by the interior furnishing (e.g. synthetic carpets, furniture with pollutant emissions). These pollutants are intolerable to asthmatics and other people with a disposition for allergies and respiratory illnesses. The quantification of these effects, however, is mostly very

difficult; their monetisation has to therefore currently be attempted using econometric methods via rents or epidemiological analyses for the respective diseases.

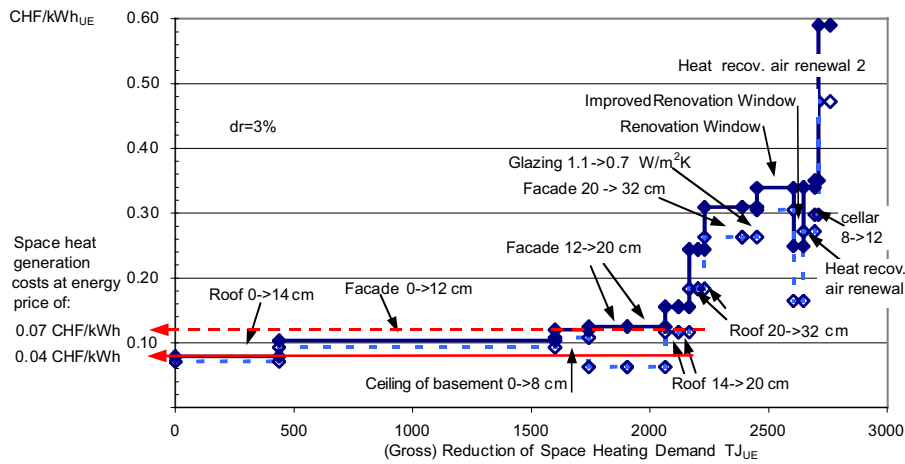
The co-benefits are also apparent from the illustration of the annual costs (see Figure 7). In particular the steep cost increase of ventilation systems becomes considerably flatter, if the additional benefits associated with a ventilation system are included and if – mistakenly – not all costs are assigned to energy efficiency alone.

### Marginal Cost Curves – The Energy Economics Perspective

First the reference for the type of new construction and the reference for refurbishment conduct had to be defined for typical cases and with regard to energetic and construction technology characteristics on the level of construction components, or rather buildings. Subsequent to this the quantitative relevance, i.e. the nation-wide frequency of these cases had to be determined. In order to do so, existing publications and statistics were fallen back upon, as well as primary inquiries carried out.

For a marginal cost curve the definition of a reference development forms an indispensable basis, as all additional investments and their associated energy savings are based on this reference. When considering the whole of Switzerland the definition of a quantitative model for future activities concerning new buildings and refurbishments becomes necessary in addition to the construction technology characterisation. For new buildings this is relatively easy; here knowledge of the future surface area for new buildings and the existing construction methods of the individual construction components are sufficient (see previous chapter). With regard to the future surface area for new buildings the views of Wüest and Partner (2000) can be drawn upon. For example, by 2010 an area of around 27 million m<sup>2</sup> is expected for single family houses and an area of 25 million m<sup>2</sup> for multiple family houses.

The investigation carried out by Wüest and Partner (2000) reports energy consumption values specifically new buildings to be around 400 MJ/m<sup>2</sup>a (includes warm water requirements and losses of effectiveness); this indicates that in practice the above-mentioned 12 cm to 14 cm are not entirely reached. Moreover, the reference case cannot be represented by a single value, as the space heating requirements have a relatively large variation. This is in contrast to the simplified approach adopted in the present analysis. However, this approximation does not significantly affect the results. The trend for advanced thermal protection, which first began in the area of new buildings, was also transferred to building refurbishments, but only in those cases in which the energy aspect was of any significance to the investor. For energy refurbishments the insulation thicknesses and the applied window qualities are generally similar to those used for new buildings. Due to construction technology conditions and construction process one's sights have to admittedly be lowered in part (no or only low insulation of those construction components adjacent to the connections, such as embrasures, edges of flat roofs or transitions between walls and roofs, as well as the base).



**Figure 8.** Marginal Cost Curve of the single family house building stock of Switzerland (construction period 1900 – 1960). With present cost level (continuous line) as well as with dynamic costs (dashed line). Source: calculations CEPE.

For the reference case the usable energy demands of buildings newly constructed by 2010 is around 7.6 PJ. For the whole of Switzerland heating requirements (on the level of usable energy) can be reduced by 1 300 TJ for new single family houses (at gross marginal costs of 0.10 CHF/kWh<sub>UE</sub>) if measures for floors, roofs, walls and windows are taken. For marginal costs of up to 0.20 CHF/kWh<sub>UE</sub> this could be reduced by a further 935 TJ. A comparatively large savings potential of 1 300 TJ of space heat demands theoretically enables the installation of ventilation systems (if ventilation systems were installed in all multiple family houses). However, the realisable portion is estimated at only 30%. The marginal costs are between 0.23 and 0.38 CHF/kWh<sub>UE</sub> depending on the situation and the heat production, if the entire costs for the ventilation system are allocated to the energy efficiency. These marginal costs must be compared to the respective heat price (long-term mean energy price divided by the efficiency of the systems). The heat price is between 0.05 CHF/kWh (present fuel prices) and around 0.10 CHF/kWh (increased international fuel prices and/or CO<sub>2</sub>-tax, or rather emissions certificates). For multiple family houses the annual space heat demand of the 25 million m<sup>2</sup> of new buildings the ERFA is around 5.6 PJ for the reference case. The space heat demands could be reduced by around 0.7 PJ, if energy efficiency investments were made for gross marginal costs of up to 0.10 CHF/kWh.

Describing the reference development in the area of building refurbishments is somewhat more complex. Next to the knowledge of the initial condition of the construction technology for the different building categories (type, construction period), additional assumptions on the refurbishment rates and versions maintenance, or rather insulation are needed with regard to the affected energy reference area, as well as with regard to the individual construction components (walls, roof, windows, cellar ceiling, etc. and their respective combinations). The empirical basis of refurbish-

ments with regard to thermal protection in the past and which could serve as a foundation for describing the development of future costs is relatively weak in Switzerland (and in most countries). Inquiries aimed at filling this gap were carried out by a research project stimulated by the CEPE. As results from this project had not been analysed before the completion of this report, provisional assumptions had to be partly made for the reference development in the refurbishment sector. Despite this reservation, the Swiss nation-wide marginal cost curves for the refurbishment of residential buildings is very informative. This is owing to the fact that a large energy efficiency potential was established at relatively low cost, particularly if a comprehensive economic assessment is applied.

This is demonstrated for single family houses from the construction period between 1900 and 1961. In the reference case the reduction of space heat demand is 7% by the year 2010 for buildings of this construction period, as next to maintenance there is good reason to additionally expect energetic refurbishments. With regard to the marginal cost curve it is assumed that within the next 10 years an additional 15% of the total of a building's walls are insulated and that the insulation thickness will be 20 cm instead of 12 cm (see Figure 8). For the roof it is assumed that in the reference case 1.5 million m<sup>2</sup> (6.5%) will be refurbished with thermal insulation of 12 cm and that for the marginal cost curve insulation thickness should be increased from 14 to 20 cm. Moreover, it is assumed that for an additional 1.9 million m<sup>2</sup> (8.3%) not only tiling and/or underfelt are renewed, but also that insulation is installed.

A considerable potential for reducing space heat requirements of approx. 1 100 TJ lies in the range of gross<sup>3</sup> marginal costs with up to 11 CHF/kWh<sub>UE</sub>. At this cost and in addition to the reference development heat requirements could be reduced by a further 9% (compared to the entire building stock of single family houses of the period from 1900 to

3. Gross marginal costs: (annualized) capital costs prior to subtracting marginal cost of heat generation (cost of saved energy plus reduced capital and O&M costs for heating systems).

1960). With gross marginal costs between 0.09 and up to 0.13 CHF/kWh<sub>UE</sub> heat requirements could be reduced by a further 3%. From these costs the saved costs from heat generation and distribution must be deducted. In the long-term these cost savings amount to 0.01 to 0.03 CHF/kWh for the heating systems and 0.04 to 0.06 CHF/kWh for the energy costs based on energy retail prices of past years and 0.08 to 0.11 CHF/kWh based on future prices<sup>4</sup>. The respective reduction potential of ongoing measures subsequently decreases and the marginal costs begin to increase significantly (see Figure 8).

If the cost decreasing potentials for 2010 due to technological progress are included, a further 500 TJ of efficiency gain (on top of the already large potential), which is achieved by insulating cellar walls and reinforcing the insulation of building exteriors, becomes economic, even if no increase in energy prices is assumed. This accounts for a further 2% of the total heat requirements of this category of buildings, or for 20% of the feasible refurbishment potential.

### Technological progress and cost dynamics

It is important for investors with large real estate portfolios, but in particular for administrative bodies and politics, that for thermal protection measures a technological-economic progress has been observed in the past. Methodologically this progress can be described by the concept of learning and experience curves. Subsequent to this new technologies are mostly relatively expensive at the start of their admission to market, but as experience shows the costs decrease by a certain percentage (mostly 10% to 20%) with every doubling of their application. Energetic measures (in particular constructional ones) show a diverse cost structure. Different deflators had to be applied to the individual cost components, in order to adjust the nominal price development estimated by the companies to the current costs, or rather different cost reductions for the cost components for the coming two to three decades. More details on cost estimates that are based on the experience curve approach can be found in Jakob and Madlener (2003).

Because of the connection between turned-over quantities and decreasing costs, future price development, as well as technological advances may be influenced to a certain degree. If energy efficiency is promoted by suitable framework conditions (temporally restricted promotion programmes, taxes, export promotion, production cooperations, pooling of demand, etc.), this will enable companies to build up experience, to initialise learning processes, i.e. to produce larger series.

### Conclusions

The present analysis of the residential buildings stock and the possible thermal protection measures with their cost structures and ancillary benefits demonstrate a complexity of the examined subject, which has been greatly simplified in previous energy economic analyses and models and by environmental interest groups. On the one hand this leads to an underestimation of the costs of conserved energy, i.e. if

only insulation material costs are taken into account. On the other hand the too simplified approach of only taking the current energy prices into account led to the observed, cliché-like valuations that heat insulation measures showed little cost efficiency and that they could only be integrated into the buildings stock if they were financially more attractive. In the contrary, the analyses suggest the following:

- Thermal insulation measures in buildings with previously non-insulated building envelopes (walls, roofs or cellars) are profitable in most cases, especially if the building owner includes a highly probable increase in energy prices during extended periods of use and the ancillary benefits in his business economic assessment.
- From an energy-economic point of view additional insulation measures are cost-efficient because ancillary benefits, which cannot all be acquired privately (e.g. avoided costs caused by illness or by loss of earnings), as well as avoided external costs with regard to conventional air pollutants (in the range of 0.008 to 0.034 CHF/kWh) and to greenhouse gas emissions (in the range of 0.045 to 0.08 CHF/kWh have to be included in the consideration).

Not investigated in this analysis, but nevertheless worth mentioning, are the further benefits from an energy economic and a macro-economic point of view. This includes the substitution of energy imports with efficiency goods and services produced in the own country, the re-availability of saved energy costs for other economic activities (rebound effect) and newly possible innovations, cost decreases and exports opportunities (politically induced techno-economic progress), as well as additional employment, also in rural and laggard regions.

From the point of view of the present or future private residential building owners and real estate investors it is necessary to be far-sighted with regard to thermal protection; the (mostly constructional) investments have a very long technological and economical lifetime from three to more than five decades and it is substantially more expensive to install thermal protection on a later occasion (up to a factor of 3). A generous thermal protection system has very low risks and, considering the increasing energy prices, can be described more as an insurance policy, because the marginal cost curves are relatively flat in the area of current energy prices. As the ancillary benefits - which are often not monetised or to which not even any attention is paid- can be of the same order of magnitude as the reduction of heating prices, the authors recommend that these cash-value effects should receive more attention. The induced increase in the value of buildings, or rather the improved leasing potential of thermally insulated buildings, is not included in the economic equation of heat protection measures, but is of fundamental significance for investment decisions due to ever-changing framework conditions (assessment of credit-worthiness by banks, ageing population).

From an energy economic and climate policy point of view building refurbishments and their large efficiency potential, which come close to being economic, deserve more

4. A long term energy price increase of 0.01 to 0.015 CHF/kWh and a CO<sub>2</sub>-Tax of 210 CHF/t CO<sub>2</sub> is assumed, see also Jochem and Jakob (2002).

attention. In comparison to other environmental and climate protection costs building refurbishment in particular, but also the construction of new buildings, offer large potentials to comparatively low or even negative marginal costs (i.e. profits), especially for renewal as opposed to maintenance.

Based on the results of this study the following tools and measures stand to reason, in order to develop the existing potentials:

- The definition of construction standards and their regulation (their legal implementation and control) has effects on several levels: (i) it helps to reduce the specific energy requirements of new buildings with each tightening of standards (ii) it informs about construction practices and identical construction components (e.g. windows, improved insulation materials, rationalised installation) and (iii) it also causes a reduction of the energy requirements of the existing building stock. On the other hand the standards promote new technological solutions and techno-economic progress through learning and economy of scale effects resulting in further cost reductions for producers and installation businesses, thereby creating new markets. A regular tightening of the construction standards according to technological developments is therefore indispensable.
- Standards and labels of associations, such as MINERGIE play an important role as pioneer and impulse carriers for producers, environmentally friendly building owners and architects, and thus have an innovation stimulating effect, serve as benchmarks, result in market transparency, but also serve as experimentation field for the next tightening of the construction standards and requirements?
- The avoidable external costs of energy use due to improved thermal protection are in the range of a few cents of CHF per kWh and the achievable additional co-benefits, which are not privatised, legitimise further federal framework conditions of a fiscal or policy nature, for example the introduction of tax (e.g. the CO<sub>2</sub>-tax of the CO<sub>2</sub> law). Adjustments to the tenancy law, which does not consider the accompanying benefits (noise protection, improved indoor air) from the view of the tenant, is also urgently required, in order to overcome the user/investor dilemma. The communication of net rents (including extra charges) is a first step in this direction.
- The results of this study are very extensive with regard to costs and energetic benefits; they could be processed further and analysed through additional detailed practical examples for individuals and for a target audience (e.g. architects, builders, house owners and interested groups), as well as for communication channels (documentation for further education, information leaflets, technical journals, construction magazines).
- The extent and the monetisation of the ancillary benefits and co-benefits of thermal protection measures are barely known and poorly analysed. In order for these benefits to be naturally included when making investment decisions, further research is necessary in this area (in the meantime the programme „Energiewirtschaftliche

Grundlagen“ (EWG) (energy-economic foundations) of the BFE are tackling this issue in a project).

In general the results give reason to be optimistic because the innovation loop “standards/innovation/cost reduction”, the imitation and diffusion of the standards for new buildings by the renovation investments and the future inclusion of ancillary benefits form promising starting points for a sustainable development in the residential buildings sector.

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## Glossary

A	Area of the building envelope, weighted according to SIA/380/1
CHF	Swiss Francs, currency of Switzerland. 1 CHF, approx. 0.67 Euro, 1 CHF, approx. 0.67 US\$, periode 2002 to 2003.
ERFA	Energy reference floor area. Sum of the heated floor areas.
FE	Final energy (energy input)
g-Value	Fraction of solar energy that transmits through transparent construction elements into the building (-), $g=1$ if 100% of the solar energy that hits the element gets into the building, $g=0$ for non-transparent elements.
HP	Heat pump
mc, ac	marginal cost, average cost (also termed project marginal costs)
Qh	Specific space heat energy requirement per heated floor area unit ERFA, (MJ/m <sup>2</sup> a)
UE	Useful energy (energy demand, e.g. space heating requirement, exclusive of conversion losses of heating systems)
U-Value	Heat loss per time and area unit and per temperature difference (W/m <sup>2</sup> K). The gross energy requirement for space heating is obtained by multiplying the U-Value with the heating degree days.
YoC	Year of Construction

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