



Marginal costs and co-benefits of energy efficiency investments The case of the Swiss residential sector

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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 marginal costs of energy efficiency investments (i.e. additional insulation, improved window systems, ventilation and heating systems and architectural concepts). For the private sector, first results on the economic valuation of co-benefits such as improved comfort of living, improved indoor air quality, better protection against external noise, etc. may amount to the same order of magnitude as the energy-related benefits are given. The cost–benefit analysis includes newly developed technologies that show large variations in prices due to pioneer market pricing, add-on of learning costs and risk components of the installers. Based on new empirical data on the present cost-situation and past techno-economic progress, the potential of future cost reduction was estimated applying the experience curve concept. The paper shows, for the first time, co-benefits and cost dynamics of energy efficiency investments, of which decision makers in the real estate sector, politics and administrations are scarcely aware. © 2004 Elsevier Ltd. All rights reserved.

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1. Introduction and scope

In Switzerland—like in many other countries of the temperate zone—large and mostly untapped energy efficiency¹ potentials lie, amongst others, in decreasing space heating requirements, which make up approx. 50% of the useful energy and approx. one-third of the final energy demand. Useful energy requirements for space heating of existing buildings could be reduced by approx. one-third to one-half compared to the present average value for the building stock and improvements by a factor of 5 or more 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, 2003; SISH, 1997).

In view of the objectives of the Swiss CO₂ law, which consists of reducing fossil fuel associated CO₂ emissions in 2010 by 15% compared to those of 1990, this energy efficiency and CO₂ reduction potential is of great significance. These potentials concerning buildings, in particular residential buildings, are not only significant because they are 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. Partly this is due to numerous barriers that still exist and partly due to different objective functions between private and public economy. With respect to the above-mentioned environmental goals, some additional costs might be acceptable for the public economy. But

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

from the private economy perspective, there might be a lack of profitability. This is especially the case if decision making is based on the level of investment costs (instead of annualised costs) or on short-term (energy price) considerations and if environmental aspects are excluded. In the market of rental flats (which is quite relevant in Switzerland), the investor-user-dilemma might be an obstacle for capital-intensive energy efficiency investments. Further reasons are incomplete information about cost and benefits, in particular co-benefits, lack of awareness and further socio-economic reasons (age, financial situation of the owners).

Indeed, building refurbishment with insulation² was (and still is) often neglected by house owners. Only one-quarter to one-third of the façade refurbishments carried out in the past 15 years included energy efficient 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 energy efficient refurbishments is slightly greater. For windows, this is particularly the case. The last 15–25 years; window refurbishment mostly meant window replacement and due to great technological progress only noticeably improved windows were available. But overall there is still a very large potential for lowering energy requirements of the building stock, as the share of the construction components that are not yet improved with respect to energy efficiency is still between 30% and 80%, depending on the component (roofs, walls, windows, including cellar ceilings which are common in most of the single and multi-family houses in Switzerland in contrast to most of the EU countries). In addition, the building envelope is often not completely but only partly refurbished, as the inquiries and surveys carried out on building façade and roofing companies have shown. The energy requirements of refurbished buildings therefore generally do not decrease down to the low-energy consumption levels of new buildings. However, from a construction technology point of view, it is perfectly possible to reach this low level or even a lower level.³ This has been shown by

a multitude of buildings of ‘MINERGIE’ label⁴ and ‘Passivhaus (passivehouse)’ standard⁵ and P&D projects carried out in the last few years in Switzerland, Germany, Austria and other countries (see examples in Binz and Schneider, 2000; EMPA, 2003; ZEN, 2003).

Commonly given arguments for not fulfilling the complete energy efficiency potential are the energy paradox (Jaffe and Stavins, 1994), in particular inadequate tenancy laws (Metron, 1998), (temporary) budget constraints, 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 energy and environment-related 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 potentials of serial production (economy of scale), 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. However, from a policy point of view, a comprehensive economic assessment should include this aspect of cost dynamics and how it can be influenced by policy instruments. Indeed, the literature reports on technological learning in many different fields and that policy instrument could make use of it by stimulating the learning and experience process to reach faster economic viability (see IEA, 2000; Neij, 1997). This paper takes up only very briefly, some results regarding technological learning in the

²In this paper the terms ‘thermal insulation’ or ‘insulation’ include—next to insulation of walls, roofs, etc. also more energy-efficient windows.

³Most construction elements (like walls, roofs, windows, cellar ceilings, etc.) of existing buildings can be refurbished to achieve a similar thermal quality as today’s new buildings, i.e. if insulation of 10–14 cm is added or the existing windows are replaced with such of glazing U -values of for instance $1.1 \text{ W/m}^2\text{K}$. 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 of 20 cm or even more does not 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 $150 \text{ MJ/m}^2\text{a}$, and to less than $150 \text{ MJ/m}^2\text{a}$, if attention is also paid to air renewal heat loss.

⁴Minergie (registered trademark) is a label of quality for new and retrofitted buildings that combines both the goals of living and working comfort and low demand of non renewable energy per square meter. There is a certain freedom of choice whether to meet the target value by improving the energy efficiency of the envelop or whether to use more renewable energy or heat pumps. Specific weights are associated to the different energy carriers to make them comparable. The target value for residential building for heating, hot water and electricity for heating purpose or air exchange is $150 \text{ M/m}^2\text{a}$ (see Binz et al. (2002) and www.minergie.ch or www.minergie.com (in English) for more details).

⁵The German passivehouse standard, limits the energy demand for heating to $15 \text{ kWh/m}^2\text{a}$. More restrictions are made on the tightness of the building, primary energy consumption and the required capacity. See more details on certification conditions on www.passivhausinstitut.de.

field of energy efficiency of building envelopes. More details can be found in Jakob and Madlener (2004).

During the long-lifetime of thermal insulation 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 in many countries. This leads to a more accentuated concentration of the oil production the OPEC in general and to the Middle East in particular (see European Commission, 1999). Thus, due to political uncertainties and/or oligopolistic phenomena risks of higher energy prices should also be considered in the assessment of the benefits of thermal insulation investments.

The assessment of such investments in residential buildings is not only concerned with an energy-related benefit, but also with other accompanying benefits. These so-called ancillary benefits or co-benefits include, for example, increased living comfort and operating ease, protection against external noise, 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 expressed in money terms in only few cases. However, they may benefit the real estate economy, as well as the tenants and builders and they may facilitate an appropriate and comprehensive economic assessment.

Finally from a public economy point of view, the ancillary benefits arise as avoided external costs through reduced emissions. Although these external costs could reach the same order of magnitude as the today's energy prices they are not included in the analysis presented here. Firstly, to prevent overloading the paper and secondly, because internalising these costs seems not to be an option in the near future in real-word policies of many countries even though there might be exceptions. UK policy for instance, which is currently being revised, takes specific account of 'the social cost of carbon'. Currently, it is set at £70/tonne emitted for this purpose.

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 regarding the building envelope. The goal was to create a new and differentiated empirical basis, following a non-trivial approach and including new methodological aspects. 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 energy-related benefits described (Section 2). A selection of results for the Swiss case is presented in Section 3. Then it is shown how an economic valuation of co-benefits can alter the results of cost benefits analysis, still from a business economic perspective (Section 4). In Section 5, the impact of cost dynamics on

an aggregate marginal cost curve is discussed from an energy economics perspective. Summarising conclusions complete the paper (Section 6).

2. Costing methodology of the marginal cost concept

How much more does a greater insulation thickness or a more energy efficient window cost? How much energy efficiency can be gained and what further cost reductions can be reached through additional insulation? 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 of energy conservation or for practical reasons; additional costs and benefits compared to the previously defined (discrete) efficiency step levels. The marginal cost approach is applicable for macro-economic considerations and for energy economy models, for the purpose of rational arrangement of promotion programs, for determining energy or CO₂-taxes, etc. For example, the additional costs of an insulation of 16 cm are compared to 12, 20 to 16, 24 to 20 cm, etc. are contrasted to the associated efficiency gain (reduced thermal transmission loss).
- Average cost approach, defined as additional costs and benefits compared to a reference case, see below. This approach is suitable if investment variants are compared to a reference investment, and it is used in practice, in particular, by 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 the 'project marginal cost'.

$$\begin{aligned} mc_{EE} &= \frac{dCapCost}{dD_{Energy}} \cong \frac{\Delta CapCost}{\Delta D_{Energy}} \\ &= \frac{CapCost_n - CapCost_{n-1}}{D_{Energy,n} - D_{Energy,n-1}} \\ &= \frac{a_n \cdot InvCost_n - a_{n-1} \cdot InvCost_{n-1}}{D_{Energy,n} - D_{Energy,n-1}}, \end{aligned} \quad (1)$$

$$ac_{EE} = \frac{a_n \cdot InvCost_n - a_0 \cdot InvCost_0}{D_{Energy,n} - D_{Energy,0}}, \quad (2)$$

where $CapCost$ and $InvCost$ denote the capital cost and the investment cost of the energy efficiency investment

considered, a the annuity factor and D_{Energy} 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 energy-related regulations with regard to space heating requirement of buildings (SIA 380/1, corresponding to EU-Standard SN EN832), or rather the actually realised energy-related quality of the new building which was empirically surveyed by (Brühlmann and Tochtermann, 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 energy-related quality of the original buildings (since the mentioned maintenance activities do not improve the energy-related quality of the building envelope), whereas cost reference is defined by the maintenance costs.
- *Energy efficiency refurbishment of existing buildings*: Each year a fraction of the building stock is not only maintained, but also improved in terms of energy efficiency. These energy effective 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: $U\text{-value}_{glazing} = 1.1 \text{ W/m}^2 \text{ K}$; $U\text{-value}_{wood\ frame} = 1.4 \text{ W/m}^2 \text{ K}$; $U\text{-value}_{synthetic-frame} = 1.6 \text{ W/m}^2 \text{ K}$).

Expressed in kWh, the marginal energy efficiency (MEE) that can be gained through additional insulation can be approximately calculated from Eq. (3), where U_{ref} stands for U_{n-1} . HDD denotes the heating degree days. In the case of the average energy efficiency (AEE), Eq. (3) applies as it is (U_{ref} is not replaced by U_{n-1}).

$$MEE(kWh) = (U_n - U_{ref}) \cdot 24 \cdot HDD. \quad (3)$$

The resulting U -value due to additional insulation thickness Δd is related to the thermal conductivity λ (W/mK) and to U_{ref} , the reference U -value (U_{n-1} or U_0 of the existing construction), through

$$U_n = \frac{1}{1/U_{ref} + \Delta d/\lambda}. \quad (4)$$

For transparent construction elements such as windows, the energy gain from solar heat (expressed

through the energy gain coefficient, g -value) has to be taken into account. To calculate the gained energy efficiency for the building as a whole, adequate calculation routines are used to account for interrelation effects between heating losses and internal and external energy gains. For further details, see the norms SN EN 832 or SIA 380/1.

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

- Inquiries concerning cost structure of façade and roof insulations with regard to insulation thickness, prices of glass and windows with regard to their U - and g -value, 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 energy-related effect, i.e. the energy efficiency gain (=reduction of space heating requirements) was calculated using the U -value, see Eq. (3). Linear thermal transmission effects were included since they become more and more relevant when assessing highly efficient energy measures). The building as a whole was calculated using a physics of building model (complying with SIA 380/1 and SN EN 832).
- The annual costs were calculated by the annuity method, which makes considerations for the specific lifetime of the energy measures and for interest rates (see Table 1). For relatively long economic lifetimes, which are common in the case of construction type energy efficiency investments, the interest rate sensitivity of the annuity factor becomes more and more important as compared to the lifetime sensitivity.
- 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.

Table 1
Assumed economic lifetime and resulting annuity factor for different construction type energy efficiency measures at two different interest rates

Type	Economic lifetime (years)	Annuity at 3.5% interest rate	Annuity at 5% interest rate
Roof insulation	50	0.043	0.055
Wall insulation	40	0.047	0.058
Windows	30	0.054	0.065
Air renewal system	15	0.087	0.096

As most energy efficiency measures are matters of constructional investments with low maintenance costs 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 (see Table 1). From a macro-economic point of view, a real interest rate of 3–3.5% 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 rates. This is also the reason why the (project-orientated) costs were calculated using a real interest rate of 5%.

Finally, the marginal cost or average cost of energy efficiency can be compared to the marginal benefit of avoided space heating generation and distribution costs. The marginal benefit consists of cost savings associated with smaller heating systems, but mainly of the reduced cost concerning energy purchase and it 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-lifetime 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 demand and coinciding with a decrease in production capacities for oil and natural gas in the non-OPEC states. (ii) The Swiss CO₂-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 CO₂-tax of 100 CHF/t CO₂ (66 Euro/t CO₂, exchange rate 2003) or an emissions certificate of about 70 \$/t CO₂ would cause an increase of roughly more than a half 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 cost 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 ancillary benefits of the construction-type investments and (iv) from a macro-economic point of view avoided external costs.

3. 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 inquired with regard to insulation thickness (see Fig. 1 as example). Next to the insulation material as a function of the insulation thickness, also additional cost components, such as mechanical structures, labour costs, etc. were included. The insulation thickness was varied from the currently common insulation thickness in Switzerland (10–12 cm) up to 30–35 cm. 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 as compared to the reference insulation. The remainder of the additional costs were associated with constructions, fixings (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

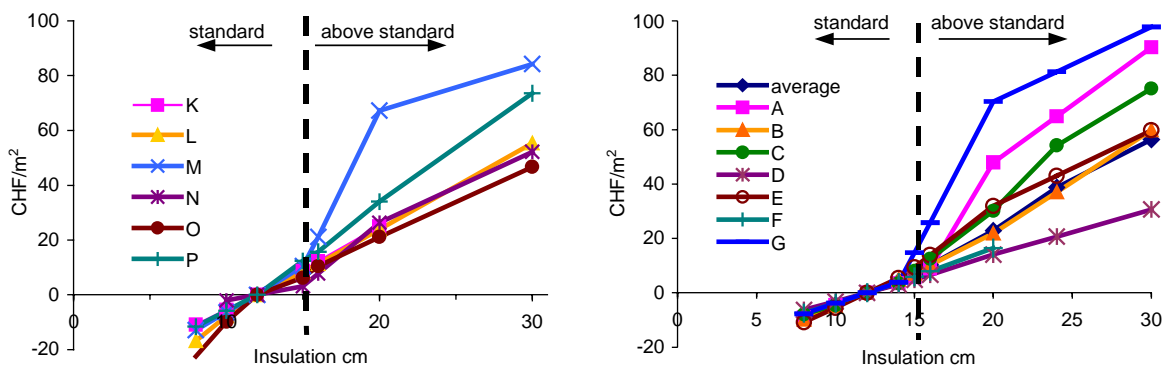


Fig. 1. Additional investment costs for wall insulations for ventilated façade (left) and a compact façade (right) compared to the reference insulation thickness of 12 cm as a function of insulation thickness. Empirical data from different Swiss building companies (tagged A–P).

connections between adjacent construction components are examined more closely, the insulation of the cill, jamb, and lintel or the roof edge may well cause additional costs during refurbishment, however, the additional energy-related effect results in marginal costs of conserved energy, which are rarely higher than the ones for area 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.

3.1. 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, which can be observed for greater insulation thicknesses (see Fig. 1). Interestingly, the price gradient (as a function of insulation thickness) is—according to the surveyed companies—more or less the same for single-family houses as for multi-family houses. 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 variation 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 a 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 2). For the reference case ER (energy efficiency refurbishment), the average costs of energy efficiency ac_{EE} of the company with the lowest (i.e. least steep) price increase (best practice) are much lower than the mean value and are therefore considerably closer to the economic viability, particularly for great insulation thicknesses. For the reference case M (maintenance), the ac_{EE} of best practice is 5% to almost 20% lower than the ac_{EE} of the companies mean and for reference case ER (energy efficiency refurbishment), the ac_{EE} of best practice is one-third to almost one-half lower than that of the mean. From an energy and climate policy point of view, it is therefore particularly effective to induce techno-economic progress through market stimulation. 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.

Fig. 2 gives an overview of the results on average cost of energy efficiency (ac_{EE}) of different construction components, building periods and reference cases. Of each data series in Fig. 2, the first data point from the left represents 12 cm (or 14 cm in the reference case of ER) and the following data points represent 14, 16, 20, 24 and 30 cm of insulation thickness, respectively. Three main insights can be inferred:

- For each of the reference cases of a certain construction period, it is apparent from Fig. 2 that the average cost curve is approx. the same for most opaque, i.e. non-transparent, construction components. This means that at certain ac_{EE} (or project marginal costs) the efficiency gain per m^2 is approx. the same. The one exception is flat roofs, where the marginal costs are clearly lower. The implication of these findings is that

Table 2

Investments of façade insulations for refurbishments and average cost of energy efficiency for single and multi-family dwellings

Insulation thickness (cm)	U-value ($W/m^2 K$)	Investment costs (CHF/ m^2)		Gross average costs (CHF/ kWh_{UE})			
		Mean	Best practice	ac_{EE} , compared to Ref. ER		ac_{EE} , compared to Ref. M	
				Mean	Best practice	Mean	Best practice
0 (Ref. M)	0.85–1.1	35	35	N/A	N/A	—	—
12 (Ref. ER)	0.28	117	112	—	—	0.061	0.058
16	0.23	127	119	0.12	0.08	0.065	0.061
20	0.20	140	133	0.17	0.10	0.070	0.067
30	0.15	174	143	0.25	0.13	0.084	0.069

Mean value of the companies and best practice, real interest rate 3.5%. Compared to the reference cases ‘maintenance’ or ‘energy efficiency refurbishment, Ref. M = reference maintenance (plaster repairs, façade coating). Ref. ER = reference energy efficiency refurbishment (12 cm external insulation), N/A = non-applicable.

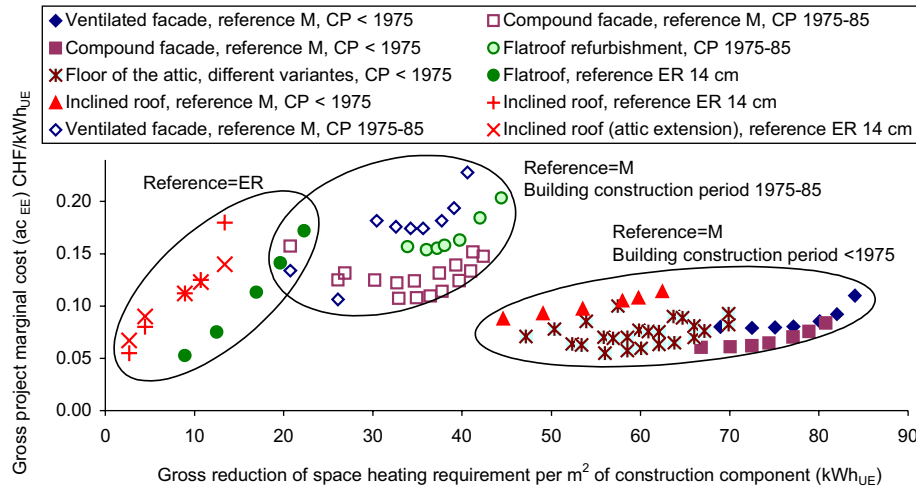


Fig. 2. Summarising illustration of gross project marginal costs (ac_{EE}) for refurbishments (reference cases ER = energy efficiency refurbishment, M = maintenance only). CP : construction period of the building.

from the cost point of view all (opaque) construction components should be insulated to roughly the same insulations thickness. Because of architectural reasons one might insulate the roof more than the façade.

- The ac_{EE} for the reference M is higher for buildings of construction periods since 1975, since the construction elements are already insulated (even though only weakly). That means that the reference U -value is already lower (0.4 to 0.6 W/m^2K) and as a consequence for roughly the same absolute investment cost per m^2 less energy efficiency can be gained, and thus the cost per kWh_{EE} is higher.
- For the reference case M (maintenance) the project marginal costs ac_{EE} are considerably lower compared to the reference case ER , especially for higher insulation thickness (low U -values). This can be understood by the fact that the efficiency gain per m^2 of refurbished construction component is considerably higher (e.g. 70 kWh_{UE}/m^2 for 12 cm compared to 0 cm and 80 kWh_{UE}/m^2 for 20 cm compared to 0 cm, while it is only between 7 and 9 kWh_{UE}/m^2 from 12–20 cm) as compared to the cost differences (see Fig. 3 remembering Eqs. (1)–(3)).

3.2. Windows and window frames

In the past, energy-related improvements of windows have been achieved particularly due to technological progress in glazing. But improved coating, different gas fillings and triple instead of double glazing can lower the currently reached standard of 1.1 W/m^2K even further. The additional costs for this are similar for both wood- and ‘plastic-’ (e.g. PVC) framed windows. There are, however, big differences between small and large windows (see Fig. 3). Large windows have lower

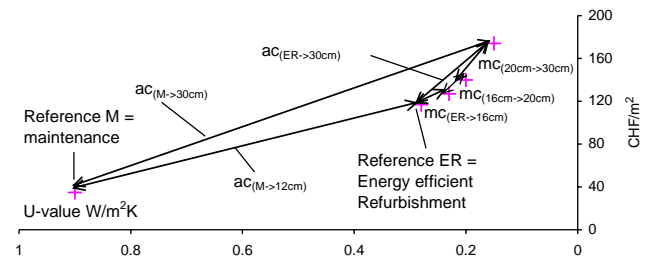


Fig. 3. Cost of façade insulation as a function of the resulting façade U -value (stylised). The average cost of EE ac_{EE} for the reference cases M and ER and the marginal cost of EE mc_{EE} are proportional to the slopes of the arrows.

reference U -values, which are due to the geometric conditions and the fact that the glass has lower U -values than the frame and lower specific costs per m^2 . Furthermore, the price increase curve as a function of increased energy efficiency windows is less steep. A large highly efficient window meeting the stringent German passive house standard can be purchased at comparable specific cost per m^2 as a small standard window. The architectural element of designing larger windows is therefore particularly economically attractive in the case of new buildings even more if the reduced cost of the wall that can be omitted by the increased window is taken account.

In the last few years, attempts have also been made to improve window frames. For ‘plastic-’ framed windows, this development is further advanced than the one for wood or wood–metal framed windows. This is expressed by a wide market supply in the area of frame quality and is also apparent from Fig. 4. 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

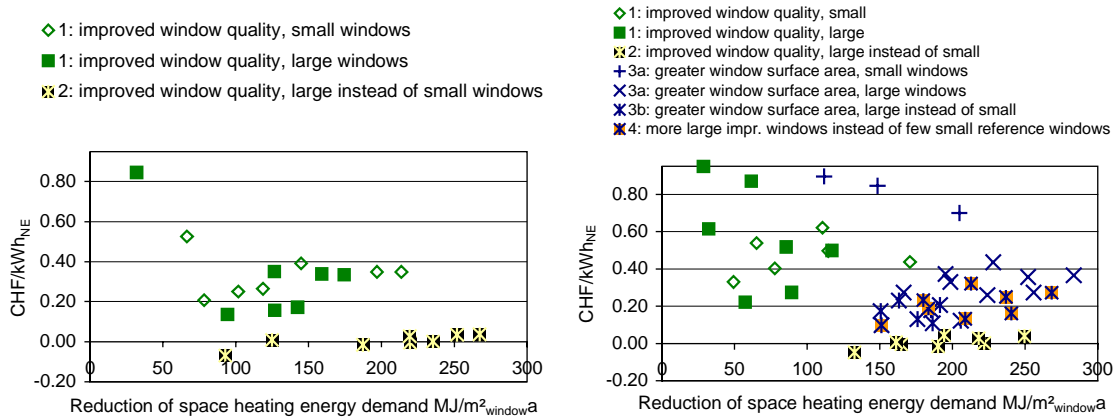


Fig. 5. Summarising illustration of the gross average costs of more energy efficient windows of alternative architectural solutions for new buildings for different cases and orientations (north: left figure, south: right figure), real interest rate 3.5%, 30 years lifetime. Source: Jakob et al. (2002).

the energy heating demand (applying the same measures) 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 may also change. It is, however, more essential that successive measures are taken for all construction components, as opposed to applying advanced measures selective to only some of the components.

In the form displayed in Fig. 6, 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 yet enable a final assessment of the economy with the inclusion of heat availability. The calculation of the system size takes place via the capacity requirement, while this, in turn, is calculated in a differentiated manner based on the actually considered building concepts. The capacity requirement usually decreases less than-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 reduced more noticeably.

At the current costs, the additional costs for thermal insulation investments cannot be entirely compensated for any system type, even if the hydraulic heat distribution of a well-built passive house can be omitted.

The costs and benefits can also be shown as annual costs with regard to space heating requirements Q_h , measured in MJ/m²a (see for example Fig. 7). This illustration method facilitates a comparison with other cost components of the housing economy, in particular with rent prices.

Table 3
Denotation of energy efficiency measures: legend of Fig. 6

Energy efficiency measure	
a	Improvement of roof insulation (U -value from 0.27 → 0.21 W/m ² K);
b	Improvement of ground floor insulation (thickness increase from 12 cm → 16 cm);
c	Improvement of wall insulation ($U=0.28 \rightarrow 0.23$ W/m ² K or equiv. 12 cm → 16 cm);
d	Further improvement of ground floor insulation ($U=0.26 \rightarrow 0.17$ W/m ² K);
e	Improvement of window glazing ($U_g=1.1 \rightarrow 0.7$ W/m ² K);
f	Further improvement of roof insulation ($U=0.21 \rightarrow 0.15$ W/m ² K or equiv. ca. 18 cm → 22 cm);
g	Further improvement of wall insulation ($U=0.23 \rightarrow 0.2$ W/m ² K or equiv. 16 cm → 20 cm);
h	Further improvement of wall insulation ($U=0.2 \rightarrow 0.15$ W/m ² K or equiv. 20 cm → 30 cm);
i	Further improvement of roof insulation ($U=0.15 \rightarrow 0.11$ W/m ² K);
j	Package: improved windows facing south, improved insulation of ground floor and basement walls;
k	Installation ventilation system with heat recovery (energy-relevant air exchange rate 0.43 → 0.13/h);
l	Windows of passive house standard facing east to north.

The total annual costs are defined as the sum of the annualised capital costs (using the annuity method) of the energy efficiency investments plus yearly expenditures for heating energy requirements. The 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/m²a) (see Fig. 6). In the illustrated example, an improvement of the specific space heat demand Q_h of around 40–60 MJ/m²a (or by approx. one quarter) can be achieved without great additional costs, even when the improbable assumption is made that the average energy price throughout the entire lifetime is only 0.055

CHF/kWh (approx. 55 CHF/100l). Space heat demands can be reduced by a total of over 100 MJ/m²a at net costs of 2–3 CHF/m², which would mean 20–30 CHF of additional costs per month for a flat of 120 m². If an energy price increase in the area of CO₂-tax is estimated at 210 CHF/t CO₂, 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 Fig. 7 were not based on best practice costs (in connection with this also note the variation in additional costs in Fig. 2 or Table 2); in future the cost increase could very possibly be more moderate than illustrated here due to growing learning and economy of scale effects. Also the non-energy related benefits, which can often be observed for further reaching energy efficiency measures (see below), have not been considered so far. In this respect, the above-described business economic net costs are incomplete and can lead to misjudgements where thermal insulation and energy efficiency investments are concerned.

In contrast to the annual costs curve which is very flat around the economic optimum (Fig. 7), see also (Hinz and Feldmann, 2001) the investment costs (e.g. Fig. 1) begin to increase immediately after the reference point,

if only marginally. Decisions based only on the investment costs will therefore not result in a construction method which is optimal with respect to energy efficiency and economic efficiency. 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.

4. Ancillary benefits (co-benefits) of thermal insulation investments

In addition to the above-described direct and indirect economic effects of energy efficiency measures, a comprehensive economic assessment has to include ancillary benefits and co-benefits. One can distinguish private and public co-benefits. In this section, the private ones are presented. In the following, some examples are used to illustrate how the inclusion of such benefits into the business economic assessment can reduce the net marginal costs (see Fig. 7):

- For the quantification of the increase in living comfort, empirical investigations on the thermal comfort were used which were based on differences between wall temperature and air temperature, as well as current conditions in the living space. It has been found previously (Fanger, 1970 and others) that a reduction of the temperature difference 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 comfort 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 conserved heating energy.
- Replacement of old double-glazed 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)

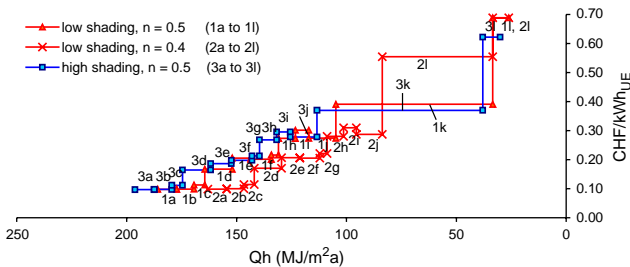


Fig. 6. Gross marginal costs for multiple-family houses (without consideration of cost reduction on the part of heat production and distribution). Parameter variation for different starting conditions of shading and of air exchange. Denotation of energy efficiency measures: see Table 3. Source: Jakob et al. (2002).

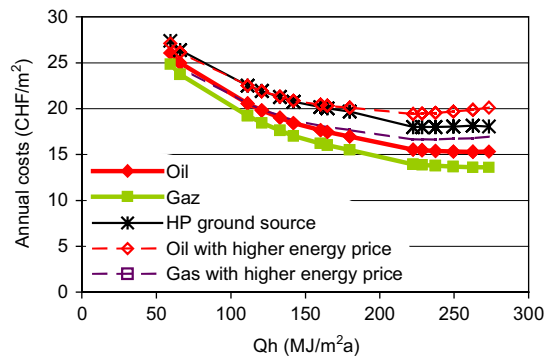
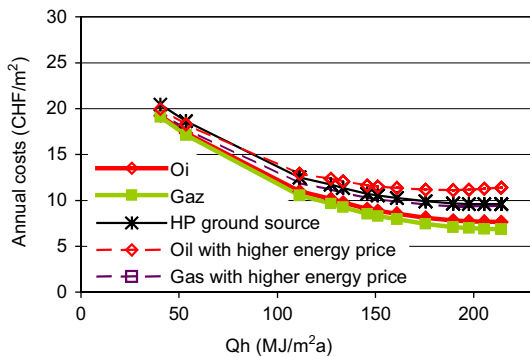


Fig. 7. Annual costs (with consideration of cost reduction on the part of heat production and distribution) for different system types for multiple family houses (left figure) and for single-family houses (right figure). Higher energy prices for oil or gas heating: surcharges of 210 CHF/t CO₂. Source: Jakob et al. (2002).

insulation material made from mineral substances, all help to reduce the transmission of external noise 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 0.6–0.9% per each additional dB by different studies (e.g. *Ecoplan, 2000*). As a rough estimation, we estimate that these economic losses are reduced by 50% if a new window replaces an old window without rubber seal. 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). Old windows reduce the level of external noise in the interior of the building by about 20–25 dB, whereas new ones achieve 33–35 dB. Even 38–40 dB are possible if (asymmetric) triple glazing is applied. Hence triple glazing offers further energy efficiency potential. Thus at noisy locations, an improvement of 10–15 dB could result in gross economic benefits (of reduced economic losses) up to the amount of 3–7% of the rental income.

- An economic analysis which was conducted recently by the bank of canton of Zurich (Zürcher Kantonalbank) using the hedonic pricing approach shows a valuation of energy efficient windows of 2–3.5% of the selling price of existing single-family houses (*Borsani and Salvi, 2003*). The same analysis reveals that new single-family houses certified with the ‘Minergie’ Label yield higher selling prices by almost 9% (with a standard error of about 5%).
- The selected examples show that for windows and roofs protection against external noise can significantly influence the profitability of heat insulation measures. Indeed direct net costs (annualised investments minus reduced energy cost) are in many cases below the mentioned benefits: Net direct cost of 2–4 CHF/m²a (see *Fig. 7*) represent 1–4% at typical rents of 100–200 CHF per square meter and per year. And net direct cost of 2–4 CHF/m²a represent capitalised costs of about 8000–16,000 CHF (capitalization factor 5%, i.e. 3.5% real interest rate, 35 years of economic lifetime) represent 1–2% at typical selling prices of single-family houses of 500,000 to more than 900,000 CHF. The total direct net costs of ‘Minergie’ buildings amount to about 7–10 CHF/m²a (equivalent to 3–7% at capitalized level) at today’s energy prices and to 3–5 CHF/m²a (1–3%) if a CO₂-tax of 210 CHF/tCO₂ were applied.
- Through improvement of indoor air quality, the use of ventilation systems has a similarly large influence on the comfort of living. On the one hand, either better air quality in flats of residential buildings located in strongly affected neighbourhoods (e.g. near

busy roads) are reached by 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 and sealed residential buildings which have excessive interior humidity (e.g. due to plants, cooking, showering while not ventilating enough) 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 generally very difficult. Expressing these effects in financial terms has to be attempted using epidemiological analyses for the respective diseases, econometric methods on revealed preferences (rental or selling prices) or empirical studies on stated preferences (direct or indirect willingness to pay). First results of a current empirical study indicate a willingness to pay for so-called comfort air renewal systems of 5% of the rental fee of apartments in new buildings (*Ott et al., 2004, forthcoming*). If this kind of benefit is deducted from the cost of the air renewal system, only the remaining part needs to be attributed to the gained energy efficiency. In doing so, the marginal cost of energy efficiency drops dramatically as indicated by the arrow in *Fig. 8*. As a consequence, the merit order of the measures could change.

5. Marginal cost curves—the energy economics perspective

The energy economics perspective differs from the business economics one, on having different optimisation goals. From a public economy and welfare point of view, optimal energy efficiency level is obtained if the marginal cost of different options (to reach a certain goal) are equal. It is important to notice that marginal costs (and not average costs) should be compared. For national goals, nationwide marginal cost curves are a suitable instrument to determine reduction potentials (of say energy demand) for a certain energy price or to determine to level of a CO₂-levy to reach a certain reduction goal. A nationwide marginal cost curve allows for an appropriate accounting of all potential measures. Knowing about the dynamics of the marginal cost curves and knowing how these dynamics can be influenced by policy instruments are other elements that distinguish the business and the energy economics perspective. The focus of this section is put on the marginal cost curve at present costs and also the

dynamics of it is touched only very briefly (see Jakob and Madlener (2004) for more insights).

To construct a marginal cost curve, first the reference for the type of new construction and the reference for refurbishment conduct is defined for typical cases and with regard to thermal and construction technology characteristics on the level of construction components, or rather buildings. Subsequent to this qualitative dimension, the quantitative relevance, i.e. the nationwide frequency of these cases was determined. In order to do so, existing publications and statistics were used, and primary inquiries were carried out (see Jakob and Jochem, 2003) since statistical data with respect to energy-related refurbishments are not available in Switzerland.

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 dwelling area of new buildings and the existing construction methods of the individual construction components are sufficient (see previous chapter). With regard to the future heated space floor area (also called energy reference floor area, ERFA) for new buildings the views of Wüest and Partner (1994) can be drawn upon. For example, by 2010, an area of around 27 million m² is expected for single-family houses and an area of 25 million m² for multiple family houses.

The investigation carried out by (Brühlmann and Tochtermann, 2001) reports energy consumption values specifically new buildings to be around 400 MJ/m²a (includes warm water requirements and conversion losses); this indicates that in practice the above-mentioned 12–14 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 more advanced thermal insulation, 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-related refurbishments, the insulation thickness and the applied window qualities are generally similar to those used for new buildings. In particular circumstances, one's sights have to admittedly be lowered due to construction technology conditions and construction process. For example, no or only low insulation may be justified for those construction components adjacent to

the connections, such as around windows and doors, edges of flat roofs or transitions between walls, roofs and the ground.

For the reference case, the usable energy demands of buildings newly constructed by 2010 is around 7600 TJ. For the whole of Switzerland heating requirements (on the level of useful energy) can be reduced by 1300 TJ for new single-family houses at gross marginal costs of 0.10 CHF/kWh_{UE} if measures for floors, roofs, walls and windows are taken. For marginal costs of up to 0.20 CHF/kWh_{UE} this could be reduced by a further 935 TJ. These marginal costs are considerably lower (almost a factor of two) if best practice is applied. A comparatively large savings potential of 1300 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_{UE} 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 cost (long-term mean energy price divided by the efficiency of the systems). The heat cost is between 0.05 CHF/kWh (present fuel prices) and around 0.10 CHF/kWh (increased international fuel prices and/or CO₂-tax, or rather emissions certificates). Depending on the assumption (average construction cost or best practice, today's energy price or increased fuel prices) a more or less significant efficiency potential can be tapped at 0 or low net cost (still excluding private co-benefits). For multiple family houses the annual space heat demand of the 25 million m² of new buildings the ERFA is around 5600 TJ for the reference case. The space heat demands could be reduced by around 700 TJ, 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 about the rate and type of refurbishment are needed. What is the quantity of construction components (walls, roof, windows, cellar ceiling, etc. and their respective combinations) that is renewed and how much energy reference area would be affected? What is the share of maintenance (such as wall painting that is not energy effective) and what is the share of energy efficient refurbishment? The empirical basis of refurbishments with regard to thermal insulation 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). As a consequence a survey aimed at filling this gap was initiated (Jakob and Jochem, 2003), but as results from this project had not

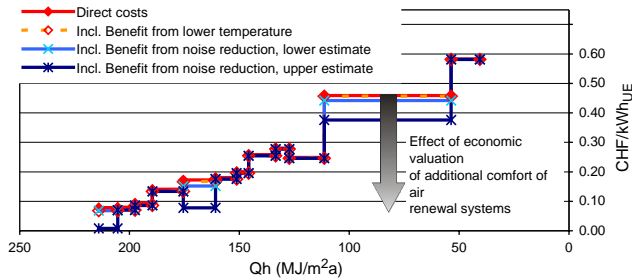


Fig. 8. Marginal cost curve for insulation investments with consideration of selected co-benefits (greater comfort, protection against external noise, better room air quality due to ventilation systems), case study with oil heating. *Source: Jakob et al. (2002).*

been analysed before the completion of the calculations of this chapter. Therefore, 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 energy-related refurbishments, as it could have been observed for the last 10–15 years. 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 Fig. 8). For the roof it is assumed that in the reference case 1.5 million m² (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 m² (8.3%) not only tiling and/or underfelt are renewed, but also that insulation is installed (Fig. 9).

A considerable potential for reducing space heat requirements of approx. 1100 TJ lies in the range of gross⁶ marginal costs with up to 11 CHF/kWh_{UE}. 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 construction period from 1900 to 1960). With gross marginal costs between 0.09 and up to 0.13 CHF/kWh_{UE} 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 0.01–0.03 CHF/kWh for the heating systems and 0.04–0.06 CHF/kWh for the energy costs based on energy retail prices of past years and 0.08–0.11 CHF/kWh based on future prices.⁷ The respective reduction potential of ongoing measures subsequently decreases and the marginal costs begin to increase significantly (see Fig. 9).

If the cost decreasing potentials for 2010 due to techno-economic 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 of the share of buildings under consideration.

5.1. 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 insulation measures, a techno-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 10–20%) with every doubling of their application. Energy efficiency 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) or in Jakob and Madlener, (2004).

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.

⁶Gross marginal costs: (annualized) capital costs prior accounting for marginal benefit of reduced heat generation (cost of saved energy plus reduced capital and O&M costs for heating systems).

⁷A long-term energy price increase of 0.01–0.015 CHF/kWh and a CO₂-tax of 210 CHF/t CO₂ is assumed, see also Jochem and Jakob (2002).

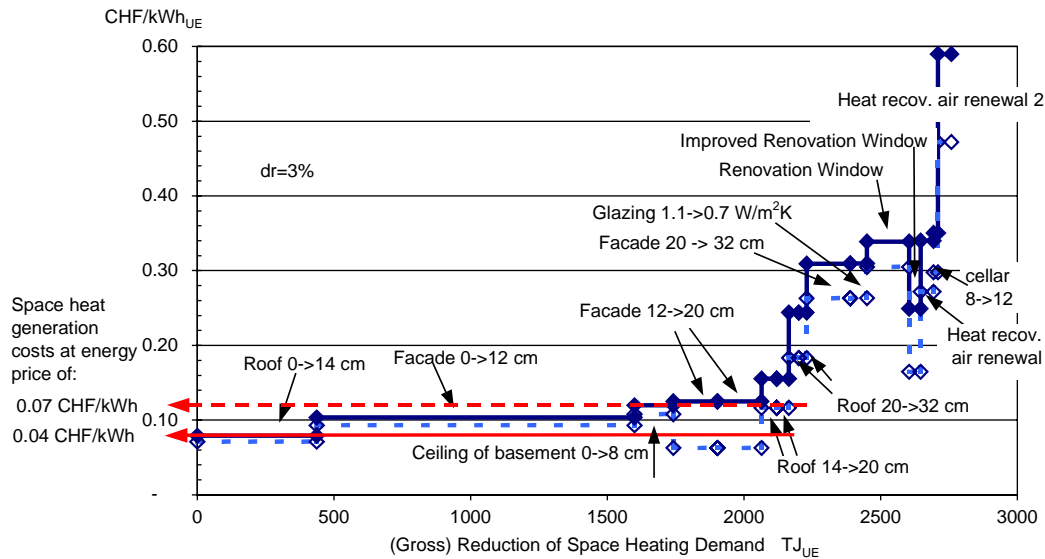


Fig. 9. Marginal cost curve of the single-family house building stock of Switzerland (construction period 1900–1960). With present cost level (continuous line) as well as with dynamic costs (dashed line). *Source:* Jakob et al. (2002).

6. Conclusions and further perspectives

The present analysis of the residential buildings stock and the possible thermal insulation 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 led 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. On 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 0.008–0.034 CHF/kWh) and to greenhouse gas emissions (in the range of 0.045–0.08 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 insulation; 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 insulation on a later occasion (up to a factor of 3). A generous thermal insulation system has very low economic risks. Considering risks of increasing energy prices, thermal insulation can be described more as an insurance policy, because the marginal cost curves are relatively flat in the area of current energy prices. The ancillary benefits—which are often not expressed in financial terms or to which not even any attention is paid—can be of the same order of magnitude as the reduction of heating costs. The authors recommend that economic valuation of these ancillary benefits should receive more attention. The induced increase in the value of buildings, or rather the improved leasing potential (rental income) of thermally insulated buildings, has not been included in the economic valuation of thermal insulation measures by most building owners, investors,

but is of fundamental significance for investment decisions due to ever-changing framework conditions (assessment of credit-worthiness by banks, ageing population). Indeed first results from Ott et al. (2004, forthcoming) based on the hedonic pricing method a price effect for buildings meeting the 'Minergie' label of 9% ($\pm 5\%$) of the selling price of single-family houses was revealed.

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 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 experiences and the developments of the last 30 years and based on the results of this study, the following tools and measures stand to reason, in order to develop the existing potentials (see also Jakob and Madlener, 2004):

- 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 the Swiss 'Minergie' label or the German 'passivhouse' standard play an important pioneer role. They give new impulses 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 insulation 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 CO₂-tax of the CO₂ 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 energy-related benefits. Including first results on co-benefits expressed in financial terms, they have been and they still are being processed further. A summarising and more easy publication for a target audience of policy makers, designers of promotion programs, architects, builders, house owners and interested groups has been produced in French and German (see Jakob et al., 2003a, b) Further channels such as the communication *campaign* 'bau-schlau' starting in 2004, documentation for further education, information leaflets, technical journals, construction magazines are suitable for further communication.
- The extent of the ancillary benefits and co-benefits of thermal insulation measures and their expression in financial terms 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. Currently (2003/2004) the programme 'Energiewirtschaftliche Grundlagen', EWG (energy-economic foundations) of the Swiss Federal Office of Energy (BFE) is tackling this issue in a research project (Ott et al., 2004).

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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Appendix Glossary

- A*: area of the building envelope, weighted according to SIA/380/1.
- CHF: Swiss Francs, currency of Switzerland. 1 CHF \cong 0.66 Euro, 1 CHF \cong 0.67 US\$, periode 2002 to 2003.
- CP*: construction period of the buildings considered.
- ERFA*: referenced energy floor area. Sum of the heated floor (dwelling) 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.
- HSFA*: heated space floor area.
- mc*, *ac*: marginal cost, average cost (also termed project marginal costs).
- Q_h*: specific space heat energy requirement per heated floor area unit *ERFA*, (MJ/m²a).
- 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/m²K). the gross energy requirement for space heating is obtained by multiplying the *U*-value with the heating degree days.