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# Exploring experience curves for the building envelope: an investigation for Switzerland for 1970–2020[1]

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**Abstract**

Energy efficiency potentials slumbering in the envelopes of existing and newly constructed buildings are significant and still largely untapped. Increasing concerns of policy-makers about non-sustainable energy use and its implications especially on climate change currently spur a growing interest in research in this area. The aim of this paper is to fill part of the existing knowledge gap by focusing on experience curve aspects of energy efficiency measures that concern state-of-the-art insulation methods, materials, and windows, and by studying the usefulness of such experience curves for the building envelope for energy policy design and evaluation. The analysis draws on a recent investigation of the situation in Switzerland (Jakob et al. 2002), but also contains a wider perspective especially regarding some more global technological trends and the market diffusion of innovative energy conservation technologies for the building envelope, policy designs, and policy programmes. The results derived from historical data analysis point to significant techno-economic progress over the last 30 years, and demonstrate the basic applicability, merits and limitations of the experience curve concept for energy policy design and impact analyses concerning the building envelope. We conclude from our analysis that building standards and labels can be important drivers for techno-economic progress, apart from the energy conservation potentials offered, and that experience curves can be a useful tool for targeted and effective policy measures and for the promotion of labels and standards.

**Keywords:** Experience curve, building envelope, energy efficiency, policy design, energy paradox

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[1] An earlier version of the paper was presented at the International Workshop 'Experience Curves: A Tool for Energy Policy Analysis and Design', IEA, Paris, 22-24 January 2003. A slightly revised version of this paper has been submitted to the *International Journal of Energy Technology and Policy (IJETP)* for a special issue on 'Experience Curves'.

# Content

# 1 Introduction

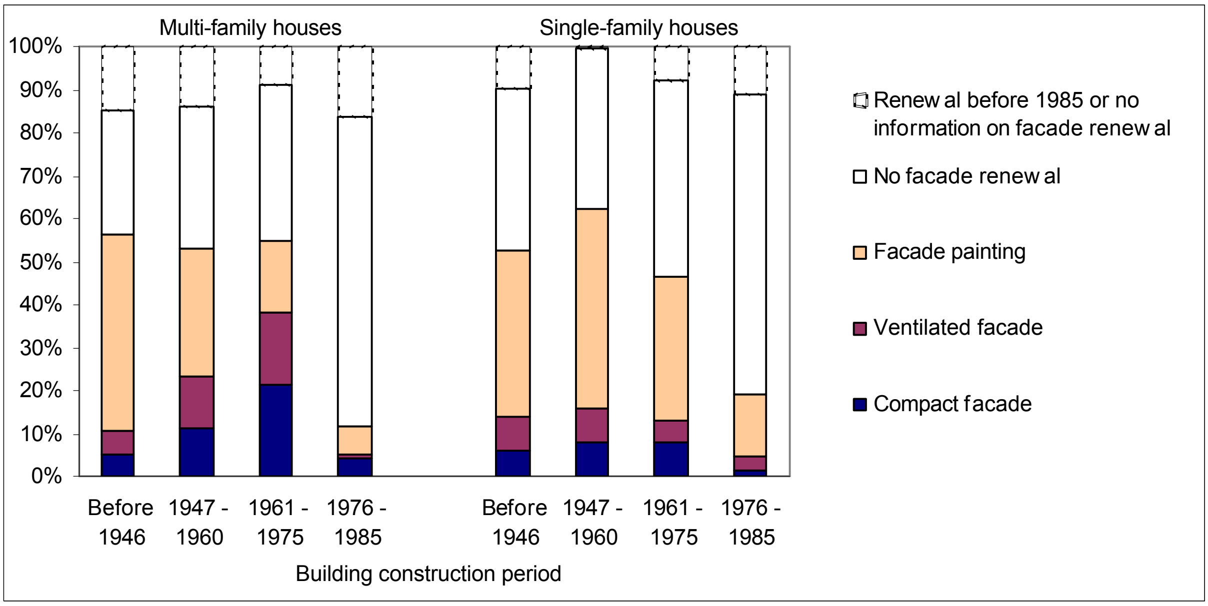
Building envelopes bear significant and to a large extent still untapped energy efficiency potentials, which strongly depend on the prevailing climatic, socio- and techno-economic, institutional, and regulatory framework conditions. Given increasing political efforts to curb unsustainable energy demand levels, e.g., in order to reduce fossil fuel import dependence, local pollutant emissions, and global greenhouse gas emissions, these potentials become the focus of heightened interest both from researchers and policy-makers alike. Until today, the scientific literature on the diffusion of innovative energy efficiency technologies related to the building envelope in general, and of experience curves that could be used for policy-making in this field in particular, can at best be described as surprisingly scarce. In constrast, one can find numerous articles from various disciplines that have focused on various aspects of energy-efficient buildings and policy measures. Among these are: Oster and Quigley (1977) (building regulation as a barrier to innovation diffusion), Hirst and Goeltz (1985) (evaluation of an energy conservation programme for residential 'weatherization'), Rosenfeld and Hafemeister (1988) (general considerations on energy-efficient buildings), Sutherland (1991) (review on market barriers to conservation measures; energy conservation in general), a series of articles provided by Jaffe, Stavins and Newell in the 1990s[2] (energy efficiency paradox, command-and-control vs. incentive-based instruments), Lutzenhiser (1994) (energy efficiency barriers arising from innovation and organisational networks in the residential housing construction industry), Marti et al. (1997) (landlord-tenant problem in the context of energy efficiency measures applied to the building envelope), Metcalf and Hassett (1997) (energy efficiency paradox analysis with monthly billing data), Hargreaves et al. (1998) (comparative analysis with thermal efficiency standards for residential buildings), Biermair et al. (2001), Lutzenhiser and Biggart (2001) (impact of market structure on energy efficiency in the commercial buildings sector), Rohracher et al. (2001) (socio-technical analysis of acceptance of ventilation systems in low energy houses), Lee and Yik (2002) (regulatory vs. voluntary approaches for building energy efficiency), Mulder et al. (forthcoming) (vintage approach with learning-by-using and diversity returns to explain the energy efficiency paradox), and Sorrell (forthcoming) (energy efficiency barriers arising from the organisation of the construction industry and climate policy as a remedy; new institutional economics perspective).

The residential and service sector alone accounts for more than 40% of the final energy consumption in the European Union (CEC 2002) and in Switzerland (Jakob et al., 2002; among others). All the more surprising is that the exploitation of the existing energy efficiency potentials hidden in the building envelopes (calculated as annualised or present value total costs of the investment minus energy cost savings) to a large extent comes at either no, or relatively low, additional direct costs. Just to give a flavour of the unexploited efficiency potentials in the building envelope: It has been estimated, for instance, that based on standard net present value investment evaluation criteria, up to two thirds(!) of the energy demand could be reduced by energy efficiency measures that are either cost-efficient or nearly cost efficient already today. Particularly, for existing buildings built prior to 1980 it has been estimated that about 30-50% of the energy consumption could be conserved with measures that can be considered cost-efficient (reduction from 450 MJ/m$^2$a to 250–300 MJ/m$^2$a), and an approximately additional 20-30% would come at low cost. For new buildings an estimated 20-30% of the measures can be realised at low cost (Jakob et al. 2002; Binz and Schneider 2000).

[2] For example Jaffe and Stavins (1995), Jaffe, Newell, and Stavins (1999), or Newell, Jaffe, and Stavins (1998).

However, many barriers still exist, and even seemingly 'no-regret' (or 'minimal regret') options, i.e. options that are basically cost-efficient if judged by standard economic investment evaluation criteria, yet remain under-utilised (so-called 'efficiency gap' or 'energy paradox'; e.g. Jaffe and Stavins 1994; Thompson 1997). One such barrier is that in contrast to investments in energy conversion technologies, investments in the energy efficiency of the building envelope typically have an 'add-on' character, in that they are not absolutely essential for the basic functioning and utilisation of the object, and thus tend to be less in the main focus of architects, planners, and investors. Another important barrier for rapid energy efficiency improvements in building envelopes is the slow turnover of the very long-lived nature of the building stock, and that by far not every refurbishment of the building envelope is done from the perspective of achieving some energy efficiency improvements. In Switzerland, for example, over the last 15 years 45–60% of the façades from buildings erected prior to 1975 were renewed. Most of the renewals, however, comprise of façade painting only. Consequently, the share of façade renewals with energy conservation relevance is rather low for most of the building types, although it can differ significantly between the various building construction periods and building types considered (cf. Figure 1). A number of barriers and driving forces exist that influence the development of this share: Barriers comprise budget constraints, landlord-tenant dilemmas, protection of the appearance of outstanding buildings, etc. Driving forces comprise certain construction deficiencies of buildings (this is true mainly for buildings erected between 1947 and 1975, where mould can be a severe problem), comfort considerations, active building stock management, but also economic considerations (e.g. prevention of accelerated economic degradation).

**Figure 1** Renewal of residential houses' façades in Switzerland, 1986-2001 (in %)




Source: adopted from Jakob et al. (2002)

Notes: Ventilated and compact façades are both outer wall insulation technologies. Whereas the former allows the control of humidity by some air circulation flow between the insulation material and the building, and offers a higher degree of damage protection, the latter consists of compound insulation materials and is less costly.

A remedy to these from an energy efficiency perspective under-exploited potentials could be that additional net ancillary or co-benefits created on top of the energy savings[3] – such as increased comfort of living, protection from external noise, an improved net present value of the real property, or lower health damages due to lowered energy demand and related pollutant emissions – also ought to be taken into account when assessing the cost efficiency of energy efficiency measures in buildings (e.g. Jakob et al. 2002; see also Jochem and Madlener 2002; IPCC 2001; OECD 2000).

The assessment of energy efficiency measures for the building stock is a rather complex subject matter. The impact and interplay of materials and building components used, decision problems and practices arising when considering the construction of new or the refurbishing of old buildings, landlord-tenant dilemmas, and other factors need to be properly addressed. Data availability is often scarce and situations and experiences in one country or region only transferable to a rather limited extent to others because of differences in climatic conditions, building codes and insulation standards, construction costs, tradition, etc.

Experience curves provide a useful – and in public policy still widely under-utilized – analytical tool for assessing the historical and expected future performance of technologies in markets, and can help to shape energy, environmental, climate change, and other policies[4].

In this paper we analyse technological progress and marginal cost developments for energy efficiency measures related to the building envelope, drawing heavily upon some of the results gained from a recent and extensive techno-economic study for Switzerland (Jakob et al. 2002). In particular, we study learning effects concerning innovative products (e.g. materials, construction elements) and processes (e.g. concerning production, planning, logistics, and mounting) relevant for a more energy-efficient building envelope, including windows. The results from our analysis are then put into a somewhat broader perspective, in order to improve our understanding of experience curves related to a more energy-efficient insulation of the building envelope, and their potential to provide some guidance in policy-making. Many of the insights gained from the Swiss experience and prospects can be adapted to other countries, provided that the differences in the framework conditions are appropriately taken into account.

The paper is organised as follows: Section 2 deals with the peculiarities of applying the experience curve concept to energy efficiency technologies applied to the building envelope (e.g. windows, wall insulation). Section 3 provides an overview of the historical experience that has been made in Switzerland over the last three decades in terms of the legal and institutional framework and the techno-economic progress made. Section 4 addresses the present situation and provides an outlook on expected developments for the next 20 years. Section 5 covers policy implications from the insights gained, while Section 6 concludes and delivers some policy recommendations.

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[3] *Ancillary benefits* indicate (usually monetised) effects that arise incidentally to certain policies, while *co-benefits* signal (usually monetised) effects that are explicitly taken into account as part of a particular policy.

[4] Pioneering work on the experience-curve phenomenon has been undertaken by the Boston Consulting Group in the 1960s (BCG 1968), based on earlier studies done, for example, by Wright (1936) on the aeroplane industry. BCG defined the term 'experience curve' for curves that relate total cost and cumulative quantity, a definition that we will also follow here. For more recent work see for example IEA (2000) and Neij (1997).

# 2 Riding the experience curves for energy efficiency technologies applied to the building envelope

## 2.1 Cost reduction potentials through economies of learning and of scale

Energy efficiency investments concerning the building shell often consist of a combination of industrially fabricated products on the one hand, and the installation/application/mounting of these products on the construction site on the other hand. Depending on the relative cost share and the stage within the innovation cycle, different experience curve effects prevail. Whereas for the first cost component mentioned, economies of mass production and economies of manufacturing plant scale are typically more important, for the second cost component learning effects as such dominate. However, the learning component can be important (as compared to mass production and plant scale) also for the fabrication of products, especially if they are at an early stage of innovation (e.g. high insulation thickness, wood-based compound material window frames, vacuum-based insulation panels, foil-inserted glazing).

Table 1 provides an overview on the relative importance of the different categories of techno-economic progress of energy efficiency and end-use technologies used for buildings.

## 2.2 Application of the experience curve concept to the building envelope

Usually, experience curves describe the relation between specific costs of energy generated (or converted) and the cumulative output of the generating or converting technologies studied, measured in units such as kW, or number of units produced, and the like. In contrast, energy efficiency technologies and measures do not provide energy, but rather help to conserve it, which calls for the definition of a reference (or baseline) for the measurement of the amount of energy conserved, or energy efficiency gained, respectively.

The cumulative area of façades on which state-of-the-art heat insulation has been applied, for instance, could be a measure for the cumulative output of energy efficiency investments. However, such a measure would not take into account the increasing energy efficiency of the façade insulation applied. As a matter of fact the costs and energy efficiency of a particular insulation measure for the building envelope including windows depend mainly on the U-value and the thickness of the material used, respectively[5]. Also, over the last decades insulation thicknesses and energy efficiencies of windows changed gradually and not in major discrete steps. Consequently, the energy efficiency has to be included into the characterisation of the specific cost and/or of the cumulative output. Table 2 shows the differences between energy conversion technologies and energy efficiency measures/technologies relevant to the building envelope.

[5] The U-value is a measure for the thermal loss of materials or components used in the building sector. It is measured in $W/m^2K$. Note that although the energetic quality of a particular efficiency measure cannot be derived from the insulation thickness alone it is a very good indicator for the estimation of the U-value (gained).

**Table 1** Assessment of the actual and future (until approx. 2020) cost reduction impacts of selected investments in heat insulation and energy conversion technologies (+++ major, ++ medium, + minor)

| Technology categories and selected examples | Learning effects* | Economies of mass production | Economies of plant scale |
|---|---|---|---|
| Building envelope / Heat insulation | | | |
| - 'Traditional' insulation materials (mineral fibres, polystyrene/polyurethane foams) | + | + | + |
| - 'Traditional' window glazing (double/triple)** | + | + (double)<br>++ (triple) | + |
| - Innovative window glazing (vacuum- or foil-based) | ++ | + | + |
| - Design and on-site application of insulation materials, components, and auxiliaries | +++ | ++ | + |
| - Pre-fabrication of construction elements (e.g. walls and roofs for wooden buildings) | ++ | ++ | + |
| - Window frames (compound materials) | +++ | ++ | + |
| - Passive energy houses | +++ | ++ | + |
| - Vacuum insulation elements | +++ | +++ | + |
| Energy conversion | | | |
| - Boilers, burners | ++ | + | + |
| - Air renewal systems with heat recovery | ++ | ++ | + |
| - Heat pumps | ++ | +++ | + |

Source: based on expert's judgement; adopted from Jakob et al. (2002), with extensions

Notes: * Assuming targeted searches for efficiency improvement potentials. ** Improvements concern mainly the optimisation of the ratio between solar energy gain and thermal conductivity/heat loss; further heat loss reductions of the glass can only with innovative window glazing be achieved.

The cost of the energy conserved[6] not only depends on the state of the technology concerned within the innovation cycle, but also largely on the thermal quality standard actually chosen (insulation thickness, U-Value, etc.). In other words, the costs of conserved energy can be low at an early stage of innovation because the consumers' preferences call for low insulation thicknesses, whereas later on, when the cumulative output has grown further (and consequently the experience curve concept would suggest lower specific costs), they may in fact have risen because of an increase in the insulation thicknesses used (e.g. due to legal requirements, higher prices/price expectations, etc.).

[6] Note that the expressions 'cost of additional energy efficiency' and 'cost of conserved energy' are used synonymously in this paper.

**Table 2** Comparison between (cumulative) output and specific cost categories, and between electricity generation technologies vs. building envelope insulation measures/technologies

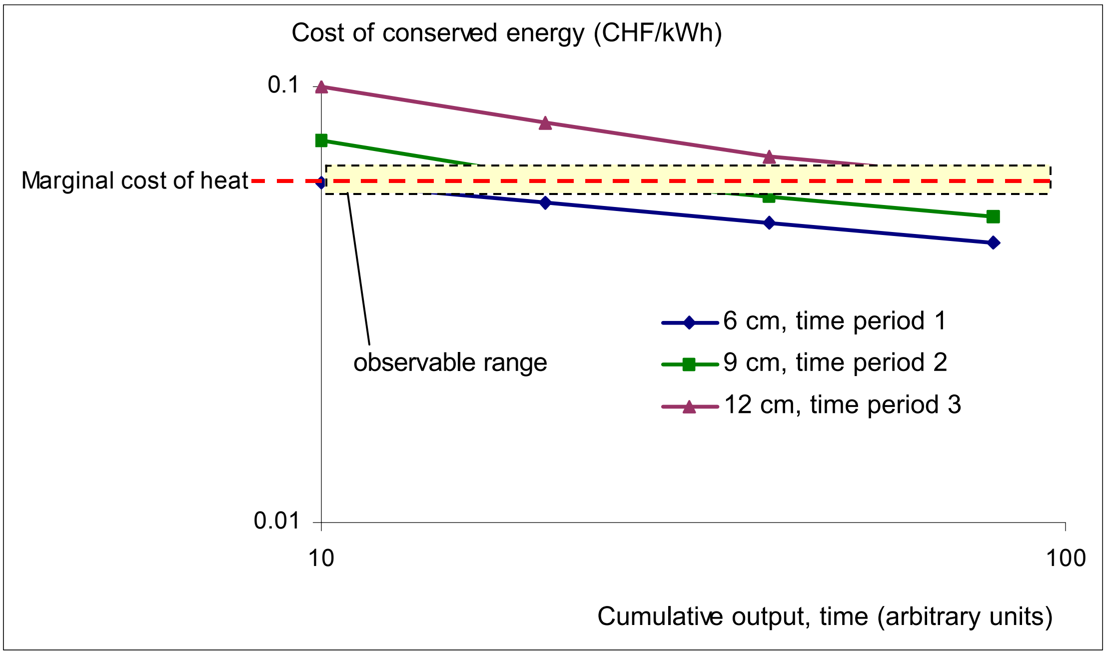
| Category | Electricity generation technologies | Building envelope insulation measures / technologies (incl. windows) |
|---|---|---|
| Output | Electrical capacity, homogenous good, independent of technical characteristics and of stage of development of the plant | $m^2$ of applied insulation or windows, energy performance depending technical characteristics and of stage of development |
| Cumulative output | • Cumulative installed capacity $kW_{el}$ | • Applied $m^2$ @ technical characteristics<br>• Cumulative $kWh_{conserved}$ |
| Specific costs | • Euro/kWe<br>• Euro/$kWh_{produced}$ | • Euro/$m^2$ @ technical characteristics<br>• Euro/$kWh_{conserved}$ |

Source: own illustration

Let us assume for a moment the ideal case where the insulation thickness is chosen in such a way that the marginal cost of conserved energy equals the marginal cost of heat generation, and that the latter would remain constant over time. In this case the economic agents would adjust the insulation thickness in line with the techno-economic progress experienced (if insulation gets less expensive, then more insulation can be applied to reach the economic optimum) and, as a consequence, the observable cost of conserved energy would remain constant over time. Likewise the observable specific costs and the insulation thickness would not follow a single experience curve but rather switch from one to another in a subsequent manner (see Figure 2). Of each of these different experience curves only a small piece can be empirically observed. Indeed, since it is already difficult to empirically determine the present marginal cost curve (or the wall insulation cost as a function of insulation thickness), for practical reasons it is sheer impossible to determine historical marginal cost curves.

The bottom line of this exposition is that the cost of conserved energy is not in every case a good indicator to be used in experience curve considerations. However, there might be cases where the experience curve concept might be applicable also for energy efficiency measures whose characteristics gradually evolve over time (such as standard wall insulation thicknesses, which increased steadily in the past). In the following sections we describe both the cases where the specific costs of energy conserved can be used. We then also propose two alternative methods for cases where they are not suitable.

**Figure 2** Experience curves for different insulation thicknesses versus marginal cost of heating (stylised)




Source: own illustration

### 2.2.1 Situation 1: Specific costs of energy conserved can be used as a measure

The specific costs of energy conserved can be used in an experience curve approach for the following two cases: First, the assessment of clearly distinguishable technologies, such as double-glazed 'insulation' windows, double-glazed coated windows, triple-glazed coated windows, etc. Second, when a new market is created or a certain standard of a technology is needed or applied due new legal requirements, independently of the marginal cost of energy conservation or heat generation. The introduction of the heat insulation ordinance ('Wärmeschutzverordnung') or the passive energy house label in Germany or the MINERGIE label in Switzerland (see sections 3 and 4 below) created new markets that made it necessary to apply innovative technologies, or more energy-efficient versions of existing products and methods. This caused an augmentation of the marginal cost of energy efficiency in the short term. Later the costs were decreasing again, and it is exactly this cost reduction process that can be assessed by the experience curve concept. In mathematical terms, these cases can be formulated as follows:

$$MC_{EE} = c \cdot Y_{cum}^{b} \qquad (1)$$

where $MC_{EE}$ = marginal cost of energy efficiency (CHF/kWh or Euro/GJ etc.)
$Y_{cum}$ = cumulative output ($m^2$, $kWh_{conserved}$ etc.)
$b$, $c$ = coefficients to be estimated

Note that if $b < 0$ an experience curve effect can be detected. The marginal costs of energy efficiency can be defined as:

$$MC_{EE} = \frac{a \cdot \Delta C_{EE}^{inv}}{(U - U_0) \cdot HDD \cdot 24} \quad (2)$$

with $a$ = annuity factor, depending on life time and interest rate
$\Delta C_{EE}^{inv}$ = additional investment costs, as referred to the reference efficiency level (CHF/m²)
$U$ = U-value of the investments considered, measured in W/m²K
$U_0$ = reference U-value (corresponding – in the experience curve concept – to the construction standard of the units considered first, e.g., wall without insulation)
$HDD$ = heating degree days

#### 2.2.2 Situation 2: Use of specific costs of energy conserved is inappropriate

If the energy quality of the building envelope is chosen according to some standard economic optimality condition (e.g. the marginal cost of energy efficiency equals the marginal cost of heat generation), or if the cost of conserved energy is even rising (implying a shift to the right on the marginal cost curve, so that per m² more energy is being saved) over time and over cumulative output despite some techno-economic progress, we propose the following alternative methods:

***Separate consideration of specific cost and technical characteristics***

If the marginal costs of (additional) energy efficiency remain constant over time, or over cumulative output, then this does not necessarily mean that there is no techno-economic progress taking place. Indeed in economics in general and for energy efficiency in particular it is often the case that technical progress leads to a higher utility level at constant cost. In these cases techno-economic progress could be described by insertion of Eq. (2) into Eq. (1), yielding:

$$\Delta C_{EE}^{inv} = c_1 \cdot Y_{cum}^{b1} \quad (3)$$

$$U - U_0 = c_2 \cdot Y_{cum}^{b2} \quad (4)$$

If $b_1$ - $b_2$ = 0 then marginal costs of energy efficiency are constant; if $b_1 > 0$ and $b_2 < 0$, then technical progress that is dependent on cumulative output (and which thus can be tackled by energy policy measures) is evident.

***Distinction between different time periods***

In any case it is important to assess the institutional, regulatory, economic, societal and other framework conditions when interpreting relations between costs, technical progress, and cumulative output. In other words, it might be a good idea to separate innovation introduction phases where the marginal costs of energy efficiency rise (e.g. due to more stringent codes and standards which first leads to higher cost but also to higher energy efficiency) from consolidation phases where a downward sloped experience curve can actually be observed.

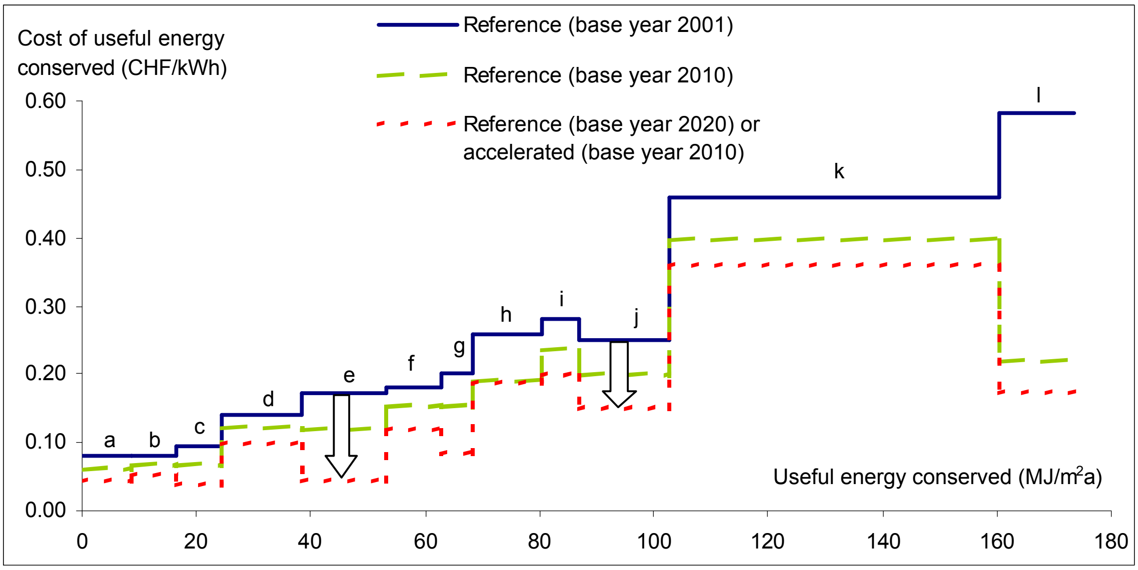
### 2.3 Marginal cost comparisons and sensitivity analysis with regard to experience curve effects

The marginal cost of energy efficiency measures addressing the building envelope, such as the improvement of heat insulation and windows, are often proportional to the (annualised) cost difference between a traditional and well-established reference energy efficiency measure and an improved (but typically less well established) measure. However, for the latter the cost reduction potential through experience and learning effects is often greater, and it is likely that the cost reductions or the technical improvements take place in a more dynamic way. Indeed, empirical evidence suggests that the time to double cumulative output is shorter and the progress ratios of new technologies are usually smaller (i.e. the learning rate is higher) than for traditional technologies. As a consequence of pure arithmetic it can be shown that the marginal costs decrease even faster: Let us suppose that the additional investment costs of improved insulation or windows are 30% higher and that the corresponding gross marginal costs of energy efficiency are 0.1 CHF/kWh (assumed exchange rate: CHF 1 = EUR 0.67). Then it follows that if the costs of some improved measures drop by 15% over the same time period as the reference measure's costs decline by 10%, the cost difference between the two (and hence the marginal cost of energy efficiency measures) decreases by 32% down to 0.07 CHF/kWh.

This phenomenon is valid for all marginal cost types where marginal costs of conserved energy are calculated as a difference of a reference investment and an improved or add-on energy efficiency measure, and where the latter have a higher and more dynamic cost reduction potential through learning and experience effects. In particular the marginal costs of conserved energy of enhanced insulation of the building envelope including improved windows confirm the existence of this narrowing gap phenomenon. At the same time the marginal costs of conserved energy by wall insulation, as compared to wall painting, behave less dynamically, i.e. only like the cost development of the reference insulation (-10% per time period in the assumed example) or – if an improved insulation is being applied – like the dynamics of improved insulation (-15% per time period).

These considerations help to understand why the marginal costs of energy efficiency (i.e. heat energy demand reduction) measures have a significantly different dynamic behaviour depending on the type of measure assessed (cf. Figure 3). Marginal costs of energy efficiency measures that have an add-on character (e.g. increase of insulation thickness, improved windows compared to standard ones) typically evolve much more dynamically than marginal costs that arise from discrete and 'lumpy' investment decisions (such as the yes/no installation of an air renewal system).

**Figure 3** Marginal costs of energy efficiency measures/technologies in relation to the achievable energy efficiency gains for the construction of a new ordinary oil-heated multi-family house in Switzerland, current cost and future or 'enforced' price paths.




Source: based on Jakob et al. (2002)

Notes: Reference energy demand for space heating: 220 MJ/$m^2$a. Ratio of building envelope area to total floor area = 1.4. The arrows denote that the merit order of efficiency measures may change over time due to techno-economic progress

Legend:

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 → 0.23 W/$m^2$K or equiv. 12 cm → 16 cm);

d = Further improvement of ground floor insulation (U = 0.26 → 0.17 W/$m^2$K );

e = Improvement of window glazing (Ug = 1.1 → 0.7 W/$m^2$K );

f = Further improvement of roof insulation(U = 0.21 → 0.15 W/$m^2$K or equiv. ca. 18 cm → 22 cm);

g = Further improvement of wall insulation (U = 0.23 → 0.2 W/$m^2$K or equiv. 16 cm → 20 cm);

h = Further improvement of wall insulation (U = 0.2 → 0.15 W/$m^2$K or equiv. 20 cm → 30 cm);

i = Further improvement of roof insulation (U = 0.15 → 0.11 W/$m^2$K);

j = Package: Improved windows facing South, improved insulation of ground floor and basement walls;

k = Installation of a ventil. system with heat recovery (energy-relevant air exchange rate 0.43 → 0.13/h);

l = Windows of passive house standard facing East to North.

# 3 Framework conditions and techno-economic progress: an overview of the last 30 years

The legal and institutional framework conditions regarding energy standards for building envelopes differ quite substantially among different European countries. These differences are, on the one hand (and not really surprising), due to the climatic differences between Northern and Southern countries. Indeed the heating period is much longer and the average outdoor temperatures are much lower in the Scandinavian countries than in the Mediterranean countries. On the other hand, however, there are as well differences among countries with similar climatic conditions, for instance between Switzerland, Germany, Austria, France, and Great Britain. It can be observed that in countries with legally binding but not very ambitious building standards new buildings are insulated much less (i.e. have a higher U-value) and windows have higher thermal losses (i.e. have higher U-values) than in countries with more rigorous standards. This is why a further harmonisation of standards within Europe was aspired (EU-Standard EN 832). The harmonisation was supported by an increased exchange of information and products within the common market, and by a general acceptance of environmental and climate protection in the societies. As a result in many European countries the insulation thickness rose considerably over the past few years (see Table 3).

**Table 3** Wall and roof insulation thicknesses in different European climatic regions and countries, various years (mm)

| | | Wall | | | | | Roof |
|---|---|---|---|---|---|---|---|
| **Climatic region** | **Country** | **1982** | **1990** | **1995** | **1999** | **2001** | **2001** |
| North | Finland | 180 | 180 | 200 | 200 | 200 | > 250 |
| | Sweden | 130 | 220 | 220 | 220 | 220 | > 250 |
| | Norway | 130 | 150 | 150 | 175 | 200 | > 250 |
| | Denmark | 130 | 150 | 175 | 175 | 175 | < 250 |
| Central | Germany | 50 | 60 | 80 | 80 | 100 | < 200 |
| | Austria | 70 | 80 | 90 | 90 | 90 | < 200 |
| | Switzerland | 80 | 100 | 100 | 120 | 120 | < 150 |
| | France | 80 | 100 | 100 | 100 | 110 | < 250 |
| | England, Ireland | 50 | 50 | 60 | 60 | 100 | < 250 |
| | Belgium | 50 | 50 | 50 | 50 | 50 | < 150 |
| | The Netherlands | 55 | 65 | 70 | 90 | 100 | < 150 |
| South | Spain | 30 | 50 | 50 | 50 | 50 | < 50 |
| | Portugal | - | - | - | - | 50 | |
| | Italy | 50 | 50 | 50 | 50 | 50 | |
| | Greece | - | - | 50 | 50 | 50 | < 100 |

Sources: see for example Ecofys (2002) and Caleb (1999), and the material made available on the MURE Website (www.mure2.com), esp. by Eichhammer and Schlomann (FhG-ISI).

In Europe, for instance, only a few large international window glazing manufacturing companies exist today. Nevertheless the different local and national subsidiaries of these international corporate groups typically do not produce their best available technology, but only the level that meets the national or regional insulation standards and/or traditions. For example, while in Austria and Switzerland coated and inert-gas-filled glazing (so-called 'heat protection glazing') almost became the standard glazing technique during the early 1990s, the market share for this kind of window in Germany was only about 10%. Only the announcement of a 'heat insulation ordinance' (Wärmeschutzverordnung[7]) in 1995 triggered the rapid and accelerated market penetration of such heat protection glazing. The rapid diffusion was supported on the supply side, because the reduction in regulatory uncertainty induced the glazing companies to invest into production facilities that enabled to produce coated glazing at much higher output rates, and – because of mass production effects and type of production effects (change from batch mode to continued mode) – at lower costs (e.g. Blessing 2001).

### 3.1 Evolution of framework conditions in Switzerland and Europe

Deeply impressed by the two oil price shocks of the 1970s and their economic consequences, authorities and professional associations in Switzerland began to worry about the increasing energy consumption of the building sector and, accordingly, tried to promote energetic improvements of the building envelope. To a limited extent energy-related improvements were also pushed by the construction industries, and partly pulled from the demand side through private and public project developers.

In Switzerland, legal exigencies for the construction of buildings vary significantly between different cantons. Nevertheless, a crude picture of the past thirty years can be provided. While the first oil crisis in 1973-74 led to a certain awareness about the importance of energy efficiency measures and some early action, only the second oil shock of 1979 led to the implementation of legally binding standards in several cantons. These were predominantly focused on individual construction elements (walls, roof, windows). In 1988, then, the Swiss Association of Engineers and Architects, SIA, published a unitary building standard (SIA Standard 380/1) on how to calculate the energy demand of buildings as a whole, and on the minimum energy quality requirements for building elements (SIA Standard 180; see also www.sia.ch and www.energycodes.ch, respectively). The standard 380/1 was accompanied by proposed limit and target values for energy demand as benchmarks. At first, only a few cantons adopted these limit and target values in their legislation, while other cantons requested less stringent values at the construction element level. At the same time some of the important and larger cantons tightened the requirements. In the mid-1990s, SIA published a reduction path ('Absenkpfad') and the federal administration encouraged the harmonisation of energy-relevant legislation for buildings (Frauenfelder et al., 1999). Meanwhile the latest edition (2001) of the standard 380/1 also contains an adaptation to European standards (SN EN 832) and serves most cantons for formulating their legislations (MuKEn 2000).

As a consequence of all this action taken, the energetic quality of the building insulation and windows applied improved continuously over the past thirty years (cf. Figure 4 and Figure 7), and the specific energy demand for space heating of new buildings has decreased accordingly. In fact the technical progress of windows developed even faster than the legal requirements or the standards that were set by the SIA.

It should be emphasised that the above-mentioned requirements only apply to new buildings or to buildings for which the envelope is being altered in a substantial way. Owners of existing buildings always were (and in fact still are) free to only maintain their building envelope (to paint their façades for instance). Despite of this caveat, a minor fraction of refurbishment also comprised wall insulation, and in those cases where such insulation was applied, the insulation level – also due to legal requirements – did not lag far behind the one of new buildings.

[7] WärmeschutzV (1995), and more recently Energieeinsparverordnung (2001).

In 1997 the MINERGIE association was founded and a MINERGIE® label (a registered trade mark) and standard were created, with the goal to promote further improvements regarding the energy requirements of buildings through labelling (see www.minergie.ch; SISH 1997; SISH 2002; for further details on MINERGIE see also section 4.1.2). It is estimated that only five years after its creation, the market share of MINERGIE buildings already reaches about 5-8% for new single-family houses. It is considered by experts that mainly two factors are responsible for the great success of the MINERGIE concept: (a) the architects' or planners' freedom on how to achieve the requirements (optimising both envelope and/or end use technology choices); and (b) the linked promotion of associated co-benefits by applying an improved building envelope and by installing an air renewal system.

## 3.2 Techno-economic progress: some empirical evidence for Switzerland

In this section we will discuss the techno-economic progress that has been made over the last three decades by providing a few illustrative examples for façades and windows. Similar improvements have been achieved for inclined and flat roofs, ground floor or basement wall insulations, as well as for (outward) doors, as can be seen from Table 4.

**Table 4** Past development of insulation thickness of different construction elements (in mm)

| Construction element | < 1960 | 1961-1965 | 1966-1970 | 1971-1975 | 1980 | 1985 | 1990 | 1993 | 1995 | 1997 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Inclined roof | | | 50 | 75 | 90 | 100 | 105 | 117 | 129 | 129 | 135 |
| Compact façade | | | | | 60-80 | 75 | 84 | | 91 | 96 | 108 |
| Flat roofs | 30 | 40 | 50 | 60-80 | 80-100 | | 110 | | 120 | | 140 |
| Basement ceiling | | | | 20 | 30 | | 40 | | | | |

Source: adopted from Jakob et al. (2002), based on data from a leading Swiss insulation producing company

### 3.2.1 Façades

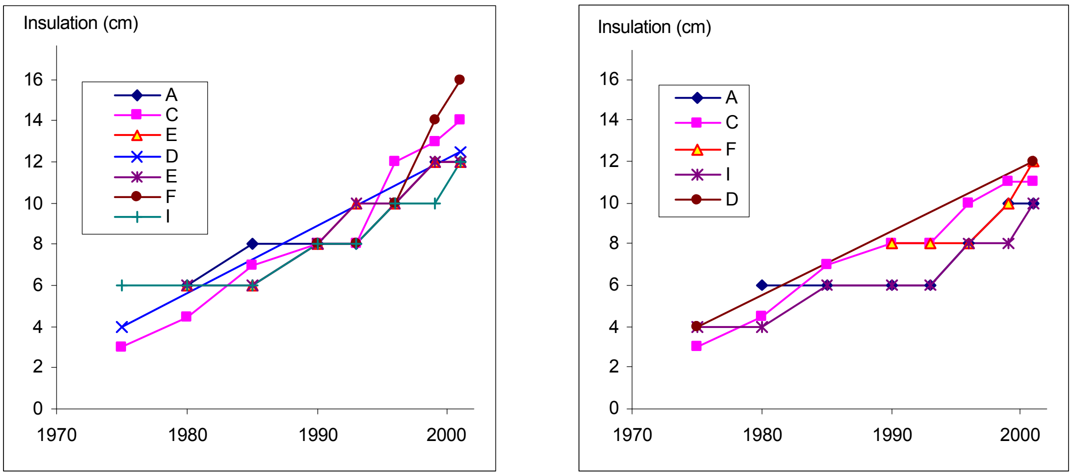
Figure 4 depicts the development of the standard building envelope insulation thickness applied by a sample of Swiss façade construction companies. As can be seen, the insulation thickness has increased by a factor of at least three(!) over a time span of thirty years[8]. As a consequence, the U-value of walls has decreased from about 0.9–1.3 $W/m^2K$ (historical value with barely any insulation) to about 0.5–0.6 $W/m^2K$ (for 4 to 6 cm of insulation) and about 0.3–0.27 $W/m^2K$ (for 12 cm of insulation). The up-scaling of insulation thickness was quite similar for new buildings and the refurbishment of existing buildings, provided some insulation was applied (many refurbishments did not comprise insulation, but only wall painting).

Apart from these similarities between new buildings and the renewal of existing buildings, important differences with respect to standards and building quality among individual building owners can be observed as well. Indeed a recent survey concerning energy consumption of a sample of more than 1'000 new buildings in thirteen Swiss cantons revealed a broad distribution of individual buildings and systematic differences between some of the cantons (Brühlmann and Tochtermann 2001). A follow-up study currently undertaken by a Swiss

[8] The development for roofs has been very similar.

consulting firm investigates the reasons for these differences and seeks for the determinants of achieved energy-related quality of buildings' constructions (Kaufmann and Dettli 2002; Econcept 2002). First preliminary evidence of this study indicates that not only the legally binding requirements influence the energy consumption of new buildings, but also the implementation and enforcement, and accompanied policy measures such as information, the support of labels, and continued educational efforts.

**Figure 4** Thickness of the standard building envelope insulation (case of ventilated facades) applied by various Swiss companies, 1970-2001




(a) new buildings (b) refurbishment of existing buildings

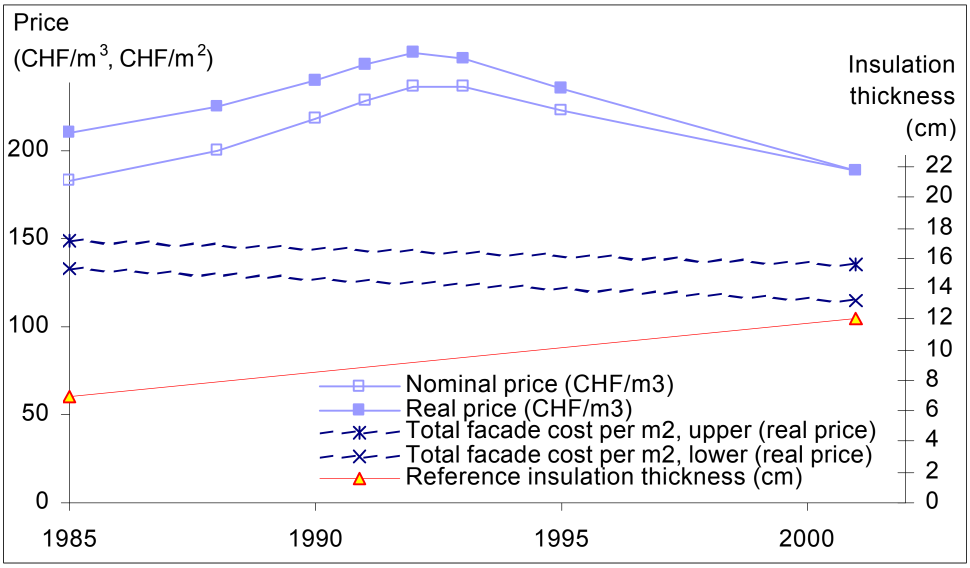
Source: Jakob et al. (2002), based on a sample survey among ten Swiss companies

Over the last 20-30 years improvements of wall insulations to meet higher standards or sterner legal requirements were mainly realised by increasing the insulation thickness, and less by the improvement of the thermal conductivity ($\lambda$-value). In recent years, in terms of their (decreased) U-value, standard insulation materials have been improved only moderately (about 20-25%). However, for innovative foam-based insulation materials (e.g. BASF's Neopor®) further improvements of between 20-40% are expected. Furthermore, public and private R&D in very promising vacuum insulation elements is currently ongoing.

Figure 5 illustrates the techno-economic progress of wall insulations that has been made in Switzerland over the past 15 years. The price increase of the insulation material polystyrene after the mid 1980s and in the early 1990s was caused by a continued boom of the economy in general, and of the real estate market in particular, but also from the higher prices for crude oil (which is an input for the polystyrene production). After 1993, continued price decreases for the insulation material could be observed. The total façade insulation costs (including the application and the connection to other construction elements) decreased as well, namely from 133–149 CHF/m$^2$ in 1985 to 115–135 CHF/m$^2$ in 2001 (real 2000 prices), while the insulation thickness increased further. From this resulted an annual decrease 0.6% in real prices per m$^2$ of façade insulated over the period 1985-2001, while the insulation thickness doubled over the same period (cf. Figure 5). Expressed in heat transmission losses of the wall as a whole, this implies a technical progress of about 3% per annum (the U-value dropped from about 0.5 W/m$^2$K to 0.3 W/m$^2$K).

By assessing the temporal development of the cost structure one can deduct that the observed total cost decrease of façade insulation was not at all only caused by a decrease in the costs of the insulation materials. First of all, the cost share of the insulation material is quite low (between 15–25%). Second, the cost of the insulation material decreased only modestly. Learning effects by the applying staff and technical progress of auxiliaries (e.g. adhesives, mechanical fixations) helped to reduce these cost components and to decrease labour assignments from 2.1 h/m² to 1.7 h/m².[9]

**Figure 5** Historical price trajectories for compact façade heat insulation made of polystyrene cellular plastics versus reference wall insulation thickness since 1985, Swiss Canton of Zurich (nominal and real 2000 prices)




Source: adopted from Jakob et al. (2002), based on an interview held in 2001 with experts from the Swiss building insulation company Marmoran AG

In order to perform experience curve calculations the yearly or cumulative output of the assessed technology must be known. Unfortunately, no exact figures about the applied square meters of façade insulation in Switzerland are available. Experts estimate, however, that the amount was roughly constant (if one ignores short term and business cycle fluctuations). Since the early 1970s the cumulative number of square meters of façade insulation doubled five to six times (and about once since 1985).

### 3.2.2 Experience curves and progress ratios for façades

In what follows, we will briefly discuss the method that has been used to derive the progress ratios, pr, for efficiency measures applied to the building envelope. The useful energy conserved and its specific costs are calculated against the reference case of a traditional wall construction with barely any energy efficiency insulation. The cost of conserved energy and thus the

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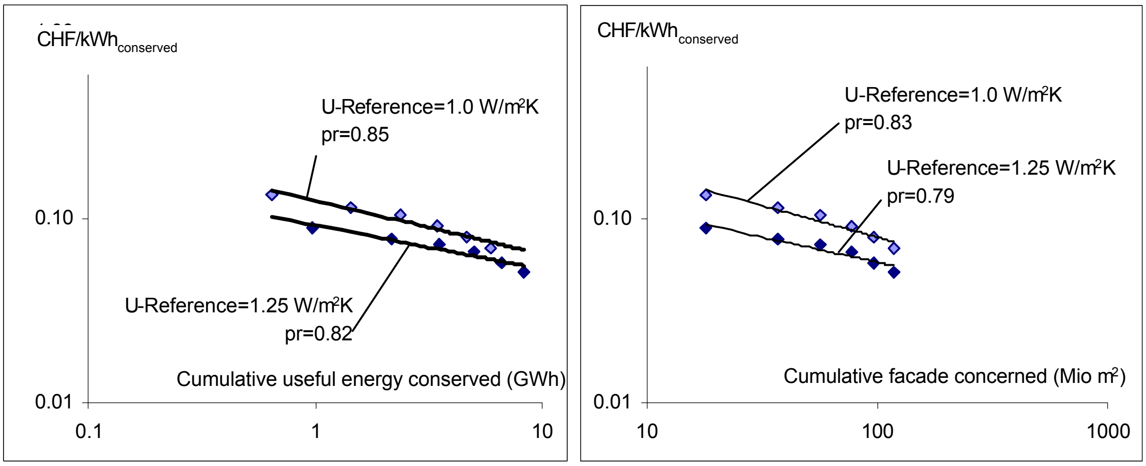
9 Methodological indication: the cost structure was used as well to perform real price calculation. For the insulation materials the producers price index was used, whereas for the rest of the costs the construction cost index for residential buildings was employed.

progress ratio depends on the U-value of the reference wall. To take into account uncertainty, two progress ratios are calculated, assuming a U-value for the reference wall of 1.0 W/m²K and 1.25 W/m²K, respectively. Hence the cost of energy conservation is calculated by subtracting non-energy relevant costs of façade application of between 35–40 CHF/m², arguing that these costs would have been necessary in any case (façade skin, connection to adjacent construction elements like windows). Each data point shown in Figure 6 represents half of a decade; the first data point stands for the 1975 situation and the last one for the year 2001.

The progress ratios found vary between 0.79 and 0.83 for cumulative square meters of façade applied as a reference, and 0.82 to 0.85, respectively, for cumulative useful energy conserved as a reference (cf. Figure 6). Note that the progress ratio referring to the cumulative useful energy conserved is lower than the one referring to the cumulative area of façade applied. This is due to a calculation artefact caused by the ongoing technical progress, which leads to more cumulative output doublings for the same time period and the same reduction of specific costs.[10]

**Figure 6** Experience curve estimation for façades, using different output categories




(a) cumulative useful energy conserved (b) cumulative façade square meters applied

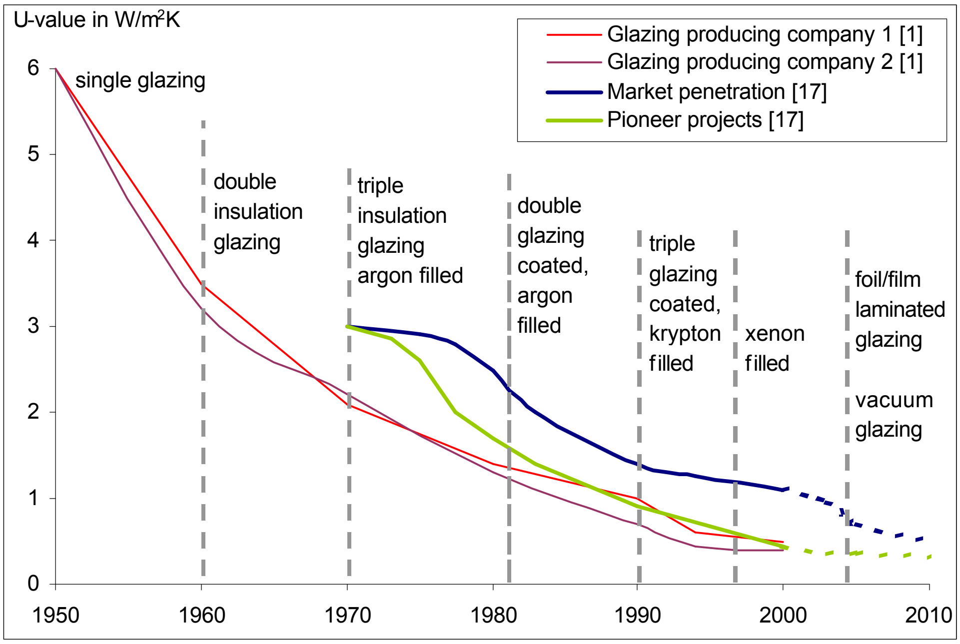
Source: own calculations

### 3.2.3 Windows glazing and windows

Windows provide a good example for technical progress that occurs over long time periods (decades) at roughly constant, or even decreasing, nominal prices. As Figure 7 depicts for window glass only (i.e. without frames), the U-values have decreased from some 6 W/m²K in 1950 (single glazing) to 3 W/m²K in 1960, and 1.8–2.2W/m²K (triple glazing, 1980s), whereas the U-values for coated and inert-gas-filled double glazing have come down from 1.3 W/m²K in 1970 to some 1.1–0.9 W/m²K (double glazing) to 0.5 (triple glazing) as of today. This is equivalent to a technical progress rate of approximately 3.3% per annum over the period 1970-2000.

[10] Apart from the assumed reference U-value, further uncertainties to deal with concern the cost of the façade application (in CHF/m²), or the cumulative quantity applied. If the applied square meters for the first three periods were only about half as much as assumed in Figure 6, the resulting progress ratio would lie between 0.85 and 0.82 instead of 0.83 and 0.79.

**Figure 7** Development of the U-values of window glazing (i.e. w/o frames) from 1950-2000 and possible future development scenario until 2010, and approximate market introduction of various window glazing technologies



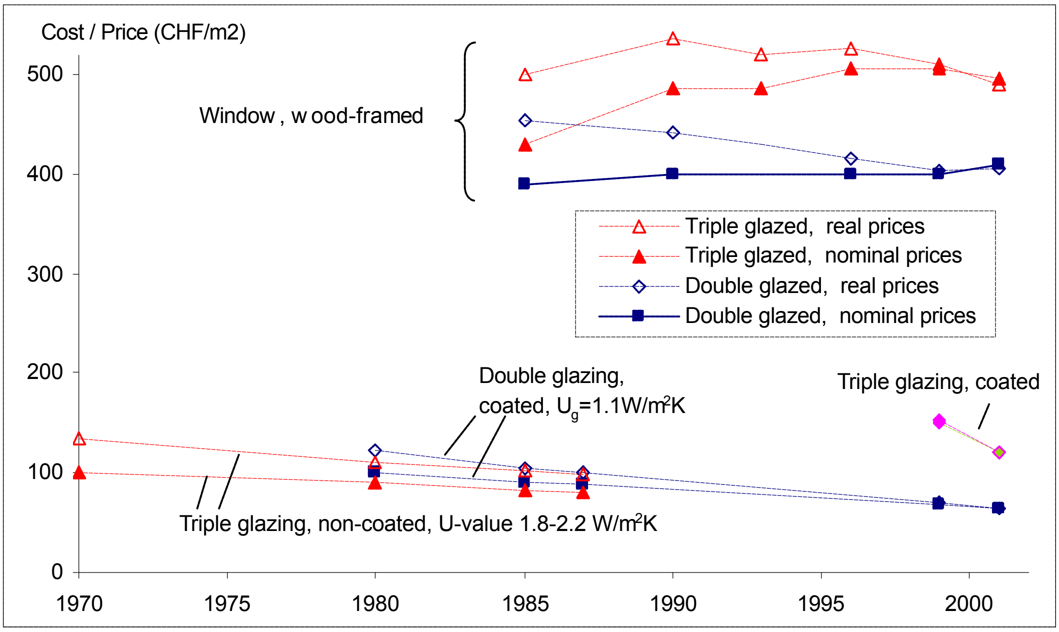

Source: adopted from Jakob et al. (2002) and Binz and Schneider (2000), respectively; based on data from two leading Swiss glass manufacturing companies

Note that the curves depicted in Figure 7 do not allow any direct conclusions for the U-value of the window as a whole, as this depends also on the area share of the frame relative to the total area covered, and also on the technical characteristics of the frame. However, in the past the U-value of the glazing very much dominated the U-value of the whole window, and only when the U-values for the glazing dropped below those for the frames (1.4–1.6 W/m²K for wood frames and 1.1–1.9 W/m²K for plastic frames), the attention paid to the frames increased somewhat. Indeed, nowadays the window and frame manufacturers need to catch up in order to keep the pace of the innovation cycle, which in the past it was primarily glazing-driven. This is especially true for wooden frames. Today's most advanced labels for energy-efficient buildings, such as the German passive energy house standard (Passivenergiehaus-Standard), actually call for significantly improved window frames, in order to allow for the window as a whole to meet the required U-value specification of 0.8 W/m²K. But the scope for innovation on the glazing side has not achieved the bottom line yet either, and news from leading R&D laboratories currently report on two basic improvement principles, viz. (a) the inclusion of one or several foils between the glasses and (b) vacuum glazing (e.g. Zimmermann and Bertschinger 2001).

Window glazing is not only predominant with regard to the technical performance of a window, but it is also an important production factor for window manufacturing underlying significant cost dynamics. As shown in Figure 8 the share of the glazing cost is about one quarter of the price paid by the end-user. Interestingly, despite of the impressive technical progress made over the last thirty years in terms of thermal conductivity, the prices for glazing have actually decreased by more than a factor of 2 (real 2001 prices). This trend has been confirmed by two other Swiss glazing manufacturers (cf. Jakob et al. 2002 for details).

The prices for complete windows remained roughly constant at around 400 CHF/m² (expressed in nominal terms), and decreased by about 10% over the last 15 years, while allowing for simultaneous improvements of various technical characteristics (e.g., energy-relevant characteristics such as the U-value, but also regarding painting and weather protection and the like).

**Figure 8** Cost dynamics for window glazing and for standard size wooden frame windows in Switzerland, 1970/1985–2000 (in real 2000 prices)




Source: adopted from Jakob et al. (2002), based on data from a Swiss glazing manufacturer and an major Swiss window manufacturer

The findings depicted in Figure 8 are in accordance with Table 5, which contains the estimation by a window and façade manufacturing association's representative regarding total cost and cost shares, respectively, of windows production. The figures show that while the cost of the glass used in window manufacturing has approximately halved from 1970 to 2000 in real terms, while the cost for material and coating and for assembly including transport has more or less remained constant, as has the contribution margin. Besides, the labour cost decreased substantially because of an increased output per employee ratio, which was enabled mainly by a transition to capital-intensive but highly efficient assembly lines. Overall, the cost of complete windows has decreased by some 25% over the last thirty years (in real 2000 prices).

Similar to other construction activities the production and assembly of windows consists of cost components of different types. Ideally deflation factors are chosen accordingly, but an appropriate deflation factor might not be available for any cost type, especially in Switzerland. In theses cases cost deflation factors of similar cost types were chosen.

**Table 5** Cost of window manufacturing in 1970 and today, nominal and real (U-value 1970: ca. 2.5–3.0 $W/m^2K$; today ca. 1.3 $W/m^2K$), expressed in $CHF/m^2$ standard window

| | Glass | Material, coating | Window manufacturing | Assembly incl. transport | Calculated contribution margin | Total |
|---|---|---|---|---|---|---|
| 1970 | | | | | | |
| - nominal | 150 | 70 | 120 | 60 | 80 | 480 |
| - real[1)] | 202[2)] | 94[2)] | 135[3)] | 80[2)] | 90[3)] | 601 |
| 2000 | 100 | 100 | 80 | 80 | 90 | 450 |

[1)] 2000 real prices
[2)] adjusted with the Swiss producer price index for the manufacturing industry
[3)] average price index for the construction of residential buildings

Source: Jakob et al. (2002), data from an interview with a representative of SZFF (Schweizerische Zentralstelle für Fenster- und Fassadenbau), Dietikon/ZH.

The historical cumulative output must be known in order to perform experience curve calculations. Experts estimate that in Switzerland the annual volume of windows sold was roughly constant over the last three decades (apart from some short-term fluctuations) at a level of about 2.6–2.9 billion $m^2$ per year. Table 6 reports then on estimations of historical market shares of windows of different energy quality (note that the time periods in the table are not equidistant).

**Table 6** Development of the relative production output (quantity-based) for double and triple glazing in Switzerland, 1970-2001 (in %)

| Glazing category | 1970 | 1980 | 1985 | 1990 | 1993 | 1996 | 1999 | 2001 |
|---|---|---|---|---|---|---|---|---|
| Double glazing insulation | 100% | 97% | 82% | 38% | 27% | 17% | 14% | 13% |
| Double glazing insulation with heat protection coating | - | - | 3% | 60% | 70% | 78% | 80% | 80% |
| Triple glazing insulation | - | 3% | 15% | - | - | - | - | - |
| Triple glazing insulation with heat protection coating | - | - | - | 2% | 3% | 5% | 6% | 7% |
| Total production volume | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

Source: Jakob et al. (2002), based on data from a leading Swiss manufacturer of insulating glasses

At least three very innovative glazing types were introduced, and the following interesting findings can be distilled:

- If needed, glazing technologies can reach high market penetration levels in a relatively short period of time: for example, coated and inert-gas-filled double glazing gained a market share of almost 60% within only five years, although other improved window types (such as non-coated triple glazing) were already introduced in the market.
- The better is the enemy of the good: after coating and inert-gas-filling had been developed and brought to the marketing stage, the already ongoing diffusion of non-coated triple glazing (that was also innovative in comparison to non-coated double glazing) was stopped

abruptly after 1985 because it was technically inferior and more expensive than the newer innovation.

In the absence of an urgent need (either economic or legal) or some special promotion campaign, the introduction of innovative technologies into the market is much slower than otherwise. Indeed, although (coated and inert-gas-filled) triple glazing was already available on the market in 1990 (2% market share), the market share has only risen to some 7% as of today. This is in great contrast to the dynamics experienced for coated double glazing after the mid-1980s, which was encouraged by general (envelope as a whole – SIA 380/1) and specific (construction elements – SIA 180) building codes.

The progress ratios calculated for the time period 1985–2001 and for double-glazed coated windows are in the range of 0.83–0.88, although due to data limitations these values should be treated with some care.

# 4 Framework conditions and techno-economic progress: the next 20 years

## 4.1 Current and expected future trends in the political, regulatory, economic, social, and institutional framework conditions

In the face of major challenges to curb energy consumption levels and especially to find low-cost options for climate change mitigation, the importance of the dormant energy efficiency potentials inherent in the construction of the building envelope has increasingly been acknowledged in recent years. The obligations entered under the Kyoto Protocol and related national policy programmes and laws are an important driving force, as are steps that have been taken to foster innovation in the building sector. For Switzerland, we will briefly mention the commitments that were made under the Kyoto Protocol (UNFCCC 1997), the Swiss $CO_2$ Act 2000 ($CO_2$-Gesetz 2000), the cantonal governments' activities, and the MINERGIE association (www.minergie.ch) as an important institution and the MINERGIE label as an important building standard for best practice.

### 4.1.1 Kyoto Protocol and Swiss $CO_2$ Act

For the period 1990 to 2008/2012 Switzerland has committed itself to an 8% reduction of greenhouse gas (GHG) emissions under the Kyoto Protocol. In parallel and as a supportive measure to the obligations entered under the Kyoto Protocol, Switzerland has committed itself in the Swiss $CO_2$-Act 2000 to reduce its overall $CO_2$ emissions by 10% until 2010, as compared to the reference year 1990. This 10% target is subdivided into a 15% reduction target for fuels for stationary use and an 8% reduction target for fuels used for transportation (excluding air traffic).

The GHG mitigation target is supposed to be achieved by means of voluntary agreements taken by industry plus other GHG-reducing activities. For the case the necessary GHG mitigation trajectory is not reached on time, the Act provides for the introduction of an optional $CO_2$ tax after 2004. This tax is capped by law at a level of CHF 210 per ton of $CO_2$ (or approx. EUR 140, based on an assumed exchange rate of CHF 1 = EUR 0.67), equivalent to approximately CHF 0.5 (EUR 0.33, respectively) per litre of transport fuel. The tax revenues will be redistributed, on a pro rata basis according to the actual split of the tax burden, among the population (per head) and industries (on the basis of the sum of wages paid).

Recently, however, it has been argued that the measures foreseen in the Swiss $CO_2$ Act will have relatively little impact on the building envelope (Ott et al. 2002). Particularly, the $CO_2$ tax levels envisaged in the $CO_2$ Act are expected to be lower than the legal cap and thus be insufficient for having any major influence on the refurbishment (and also on the investment) cycle. Besides, the rental law for housing does only allow a shift of energy-related investments in buildings onto the rents to the extent that they lead to added value (typically around 50–70%). Besides, most of the building owners are – for legal and practical reasons – exempt from a participation in the so-called 'voluntary commitment scheme'. Thus it is expected that a $CO_2$-tax would mainly urge private building owners that live in their own buildings and promoters of new buildings to reconsider their (renewal) investment decisions in direction of slightly more energy-efficient options or the adoption of the MINERGIE standard.

### 4.1.2 Activities of the Swiss cantons and the Swiss MINERGIE standard

The MINERGIE standard for residential buildings foresees maximum specific heat consumption values of 45 kWh/m² (160 MJ/m²) per annum for new buildings and 90 kWh/m2 (320 MJ/m²) per annum for buildings erected before 1990 (only fuels for heating and hot water are accounted for, electricity demand for heating and ventilation is counted double); the corresponding (additional) value for household appliance electricity use is 17 kWh/m² (60 MJ/m²) per annum.

As a reaction to rising difficulties in enforcing and tightening command-and-control measures that aim at raising the energy efficiency of buildings, some of the cantonal authorities put more weight on motivation, stimulation, and incentive-based measures. In 1997 some leader cantons co-established the MINERGIE label which strongly emphasises (a) the promotion of co-benefits of energy efficiency measures (in particular living comfort) and (b) the planners' and architects' liberty on how to achieve the energy consumption requirements (i.e. by focusing on the envelope and/or the implementation of efficient or renewable end-use energy technologies – performance-based instead of component-oriented approach).

In the year 2000 the mandate for the promotion and stimulation of energy efficiency measures in buildings was passed on from the federal authorities to the cantons (see Frauenfelder et al. 1999). Many of the cantons have since then defined MINERGIE as a prerequisite for receiving financial support for the construction of new and the refurbishment of existing buildings. Experts think that over the next eight to ten years the promotion and support of MINERGIE will be in the foreground of policy, and that the authorities will deal with a reinforcement of the building codes only afterwards. Thus MINERGIE could actually turn into a legally binding minimum requirement after a certain period of time.

Recently, the MINERGIE standard has been refined in various ways: For one thing, a minimum requirement now also exists for the building envelope (in useful energy units), and not just for the consumption of final energy. Moreover, a more ambitious MINERGIE standard has been introduced that essentially reflects the German passive house standard (so-called 'MINERGIE-P' standard; see Binz et al. 2002). Finally, an extension to buildings that belong to the service and the industrial sector has been implemented (cf. www.minergie.ch, SISH 1997 and SISH 2002).

### 4.1.3 Swiss federal energy program 'SwissEnergy' ('EnergieSchweiz')

SwissEnergy is a 10-year energy program that aims to foster the use of rational and renewable energies and in particular to achieve the climate change mitigation goals stipulated in the Swiss $CO_2$ Act (BFE 2001). The strategy is mainly based on voluntary measures and the cooperation between the public authorities and various industrial associations. Elements include:

- The use of performance contracts and general agreements;
- Promotional programmes as provided for in the Energy Law (e.g. overall subsidies granted to the cantons);
- Back-up for the voluntary measures adopted and as a supplement to the promotional programmes taken up (e.g. marketing, public relations, consulting, training, quality assurance including labels and standards, RD&D);
- Regulations (e.g. with respect to goods declarations and target values, requirements on the energy consumption of motor vehicles, appliances and buildings); and
- Incentives (esp. in the transport sector).

Besides, the MINERGIE standard and a further harmonisation of building regulations is an explicit goal of SwissEnergy.

#### 4.1.4 European policy developments regarding energy performance of buildings

At the European level, the European Commission has recently published an amended proposal for an EU Directive on the energy performance of buildings[11] aimed at complementing (and enabling more concrete) efforts in this field by a legal instrument. It can be expected to have certain spill-over effects for non-member countries like Switzerland. Its main objective is *"to promote the improvement of the energy performance of buildings within the Community, taking into account outdoor climatic conditions and indoor climatic requirements, local conditions and cost-effectiveness"* (ibid., Art. 1). The Directive proposal contains the stipulation that *"[p]rovision should be made for the possibility of rapidly adapting the methodology of calculation and of regularly revising minimum standards in the field of energy performance of buildings in order to reflect technical progress and future developments in standardisation"* (ibid., §18). As measures, the EC Directive contains requirements regarding (a) a common methodology for calculating the integrated energy performance of buildings; (b) the application of minimum standards on the energy performance of new and large existing buildings subject to major renovation; (c) energy certification of buildings; and (d) regular inspection of boilers and central heating air-conditioning, and of heating installations in which the boilers are older than 15 years (ibid., Art. 1 cont.). Exceptions apply, for example, to certain officially protected buildings and monuments, religious buildings, temporarily used buildings, and stand-alone buildings with less than 50 $m^2$ (ibid, Art. 4).

### 4.2 Established versus pioneer markets

When assessing new and innovative technologies, pioneer market phenomena can be observed. In the following subsections some empirical evidence is briefly being discussed for the case of exterior wall insulation and of windows for Switzerland.

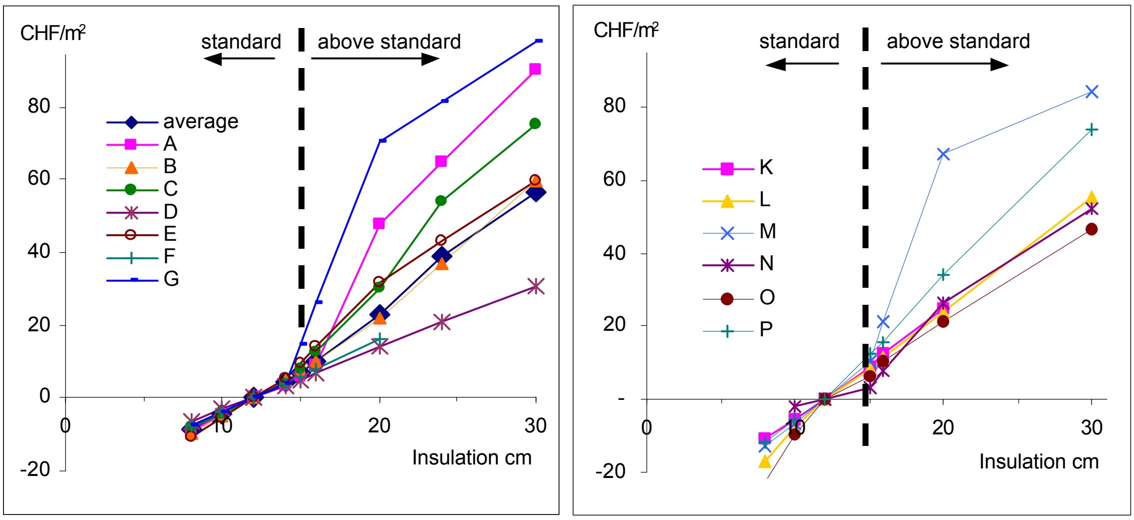
[11] Historically, the EC Programme SAVE, which dates back to 1993 (CEC 1993), has played a dominant role in enhancing the energy efficiency of buildings. For the most recent Directive proposal from the European Commission see CEC (2003).

### 4.2.1 Wall insulation

Figure 9 depicts the price differences per square meter (as referred to an insulation thickness of 12 cm) charged by various Swiss building companies, in relation to the thickness of the wall insulation used. Data were gathered in a survey in which the price as a function of the insulation thickness was asked. Thus the data do not represent actual project data, but rather systematic 'close to the market' offer prices. As can be seen, prices are quite similar in the range between 8–15 cm, which corresponds to today's most commonly used insulation thickness (conventional 'standard' range, left of the dashed lines), but they vary much stronger beyond a thickness of about 15 cm (innovative 'above standard' range, right of the dashed line). This can be explained by the following factors:

- Having 12 cm as the most common insulation thickness, more than 15 cm is applied quite rarely, and the façade companies have not yet gained sufficient know-how both in carrying out façade application and in competitive cost calculation (accounting), so that it can be safely assumed that some precaution surcharges are included in the price statements;
- The market for highly efficient building envelopes is only about starting to develop, both on the supply and the demand side. Indeed, up to now most architects and planners are not yet very well informed about best practice charges for increased insulation thickness, and so are the consumers.

**Figure 9** Prices for various wall insulation thicknesses charged by different Swiss building companies (tagged A-P)




(a) compact façades (b) ventilated façades

Source: based on Jakob et al. (2002)

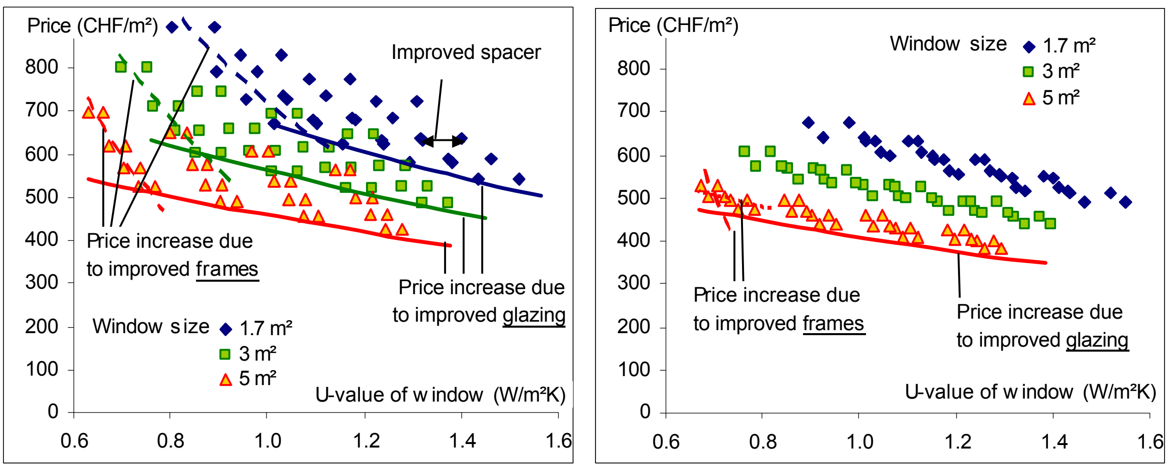
It can be expected that the more the demand for increased insulation thickness will rise and the more architects, planners and investors are informed about best practice costs, the more the prices will decline towards the bottom line of best practice prices (companies D, L, F, and O).

Note that in this case the marginal cost of energy conservation (as referred to a reference insulation thickness of 12 cm, corresponding to a U-value of about 0.3 W/m²K) would drop dramatically if the costs move from nowadays' average costs to best-case costs. For instance, Jakob et al. (2002) have shown that the marginal cost, mc, of conserved useful energy would decrease from some 0.12 CHF/kWh to 0.08 CHF/kWh (mc of 16 cm as referred to 12 cm insulation thickness) and from 0.17 CHF/kWh to 0.10 CHF/kWh (mc of 20 cm as referred to 12 cm insulation thickness), respectively, i.e. by around one third.

### 4.2.2 Windows

To assess today's marginal costs of energy efficiency (energy conservation) measures applied to the building envelope, prices of windows of different technical characteristics were also surveyed in Jakob et al. (2002). The analysis of the data gained that way enables the identification of further cost reduction potentials, similar to the wall insulation case (see above). Figure 10 reports on the prices charged for windows made with either wooden frames (subfigure (a)) or plastic frames (subfigure (b)) as a function of U-values for several frame and glass qualities and for several types of spacers[12]. As can be seen technological advances concerning the glazing used has a lesser impact on the prices for complete windows, as compared to improvements concerning the window frames. This phenomenon is much more pronounced for wood frame windows than for plastic-framed ones. Indeed, hardly any energy-relevant innovation could be observed over the last years for wooden frames, despite the fact that glazing underwent significant technical progress, so that the U-value of the glazing is now typically below the one of the frames. Reasons for little innovation in the area of wooden frames are: (a) absence of demand-pull; (b) technical/architectonical reasons (using wood only would lead to thick and unaesthetic frames); and (c) the 'micro-structure' of the windows sector (more then half of the market consists of small- and medium-sized manufacturing companies).

**Figure 10** Prices for (a) wood-frame and (b) plastic-frame windows in Switzerland as a function of window-U-values for various frame and glass qualities, various spacers and window sizes (1.7 m², 3 m², and 5 m²; frame shares 30%, 22%, and 15%)




(a) wood frame windows (b) plastic frame windows

Source: Jakob et al. (2002)

In contrast to wooden frames the innovation cycle for plastic frames has been progressing for quite some time. Primary reasons are: (a) the high U-values that have been achieved for

[12] Spacers are used as a separator of two glasses in a window glazing.

traditional plastic frames some years ago (which called for improvements, also for image reasons) and (b) the fact that due to its construction principle (re-enforced, hollow structure) the plastic frame was more predestined for further improvements. As a result the variety of U-values is nowadays much higher for plastic frames, and the costs for the window as a whole for energy-relevant improvements have become more similar between frame and glazing. Note that in the case of glazing innovation took place since 1990, despite the absence of any tightening of the specific building or window codes.

Apart from further technical improvements of the window glazing (which manifests itself in a further cost reduction for traditional triple glazing; besides, foil-insertion and vacuum-based glazing are currently under development and will be introduced to the market soon) there is an important cost reduction potential for wood frames, similar to that experienced for plastic frames. In the future innovative wood frames will not be made solely of wood, but instead of compound materials, a trend that can be identified for windows that have been developed to meet the challenging German passive house standard. A further demand for such windows and the labelling with MINERGIE would help to decrease prices, an assessment that also manufacturers agree upon.

## 4.3 Potential future techno-economic progress of wall insulations and windows

Energy efficiency measures concerning the building envelope typically consist of several cost and/or technical components. Therefore a separate assessment of the different cost components seems advisable.

### 4.3.1 Wall insulation

Table 7 shows some of the results gained recently from an explorative assessment for Switzerland on the expected cost development for compact façade heat insulation components over the next three decades (see also Jakob et al. 2002). The assumptions made are that material costs can be reduced only little by 1 CHF/m$^2$/decade until 2020 due to technical progress, after which they will stagnate because of assumed oil price rises (materials are either energy intensive or made out of oil products). Furthermore, concerning planning, assembly and scaffolding, cost reductions of 0.5% per annum have been assumed. Taken together, this would result in a (real) cost reduction potential of 5% per decade for standard compact façade constructions with 12 cm of polystyrene insulation.

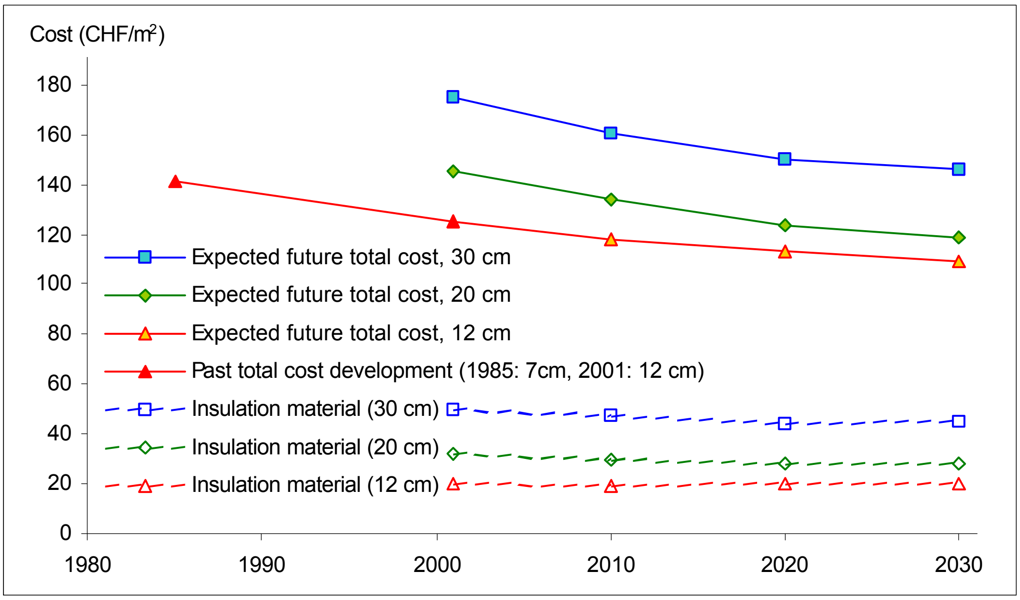
**Table 7** Estimated cost development for compact façade heat insulation (12cm polystyrene cellular plastics, in constant 2000 prices), 2000-2030

| Cost category | 2000 | 2010 | 2020 | 2030 |
|---|---|---|---|---|
| Material cost (12 cm insulation) | 20 | 19 | 18 | 19 |
| Auxiliary equipment, scaffolding, preparatory work | 20-30 | 19-28 | 18-26,5 | 17-25 |
| Assembly costs, fittings | 75-85 | 71-80 | 68-76 | 64-72 |
| Total | 115-135 | 109-127 | 104-121 | 100-116 |
| Average (in CHF/m$^2$) | 125 | 118 | 112.5 | 108 |

Source: adopted from Jakob et al. (2002)

Since insulations of more than about 15 cm in thickness are at a much earlier stage of market development and competition, it can be assumed with good reasoning that the technical progress for, say, 20 cm or 30 cm of insulation would take place at a higher rate than for standard thicknesses. It is assumed further that add-on cost (as compared to 12 cm) for planning and assembly needs and auxiliary material would decrease in the next twenty years at a similar rate than the ones for 12 cm between 1985 and 2001, i.e. at 1%/a, so that the total add-on costs (as compared to 12 cm) decrease by 0.7%/a. This leads to the total costs presented in Figure 11.

Figure 11 Difference costs for various insulation thicknesses (12, 20, and 30 cm), insulation material alone and total




Source: adopted from Jakob et al. (2002)

### 4.3.2 Window glazing and windows

The potential future cost dynamics of energy-efficient windows point to two possible techno-economic fields for progress:

- Glazing: further improvement of traditional double (advanced stage of development) and in particular triple glazing (middle stage) and new glazing innovations (inserted foils, vacuum-based glazing, both in premature stage);
- Framing: wooden and related compound material frames (early stage of development), (plastic frames) middle stage of development.

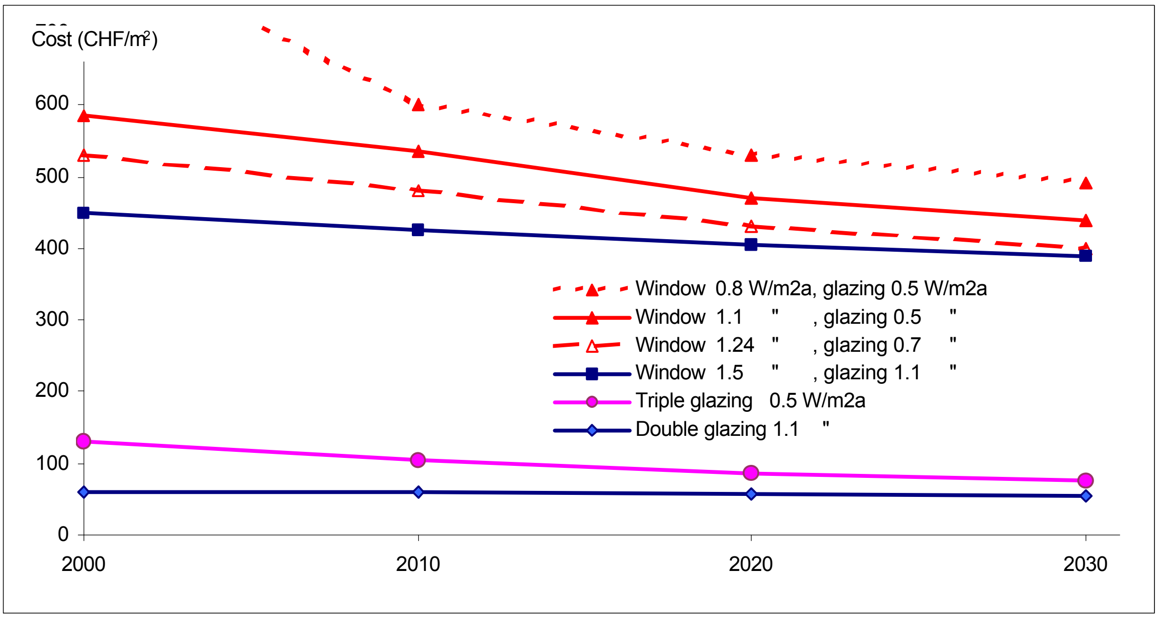
Since new glazing innovations are still in the research phase, and since they do not have a (competitive) market price yet, techno-economic and experience curve considerations cannot be applied. Thus the following explorations regarding possible cost dynamics are restrained to window products that have already diffused the market.

Figure 12 reports on the estimated costs of window glazing and windows for various glass and window qualities (in terms of their U-values). As can be seen the cost for triple glazing (coated and inert-gas-filled) decreases faster than the one of the already well-established double glazing and, therefore, the costs of the two glazing types can be expected to converge in the longer term. The same applies for total costs of triple-glazed windows (U-value for the glazing 0.7 and 0.5 W/m²K, respectively). The most dynamic cost development is expected for the windows, where frames and glazing are improved jointly, since this kind of windows is still at a very early stage of development and up to now only covers a small share of the total market size and market potential. Hence they have the greatest techno-economic improvement potential and in principle several doublings of cumulative output is possible within a few years from now.

The following assumptions were made to achieve the explorative results shown in Figure 12: for triple (coated and inert-gas-filled) glazing a progress ratio of 0.85 has been assumed (i.e. similar to the one for triple non-coated glazing after 1970), starting from a low annual output level according to Table 6 above.

Based on these assumptions, the following observations can be made for the different window types: (a) the progress ratio for wood frame windows is – as observed in the past – higher than the one for glazing. We assume a progress ratio of 0.9 (as compared to 0.85 for glazing) and, additionally, we assume that the learning and experience curve effects arise only on the window production side, and not on the side of the installation of the windows in the buildings. From this results an average total cost decrease of 0.35%/a, or a decrease from 600 CHF/m² (2000) to 540 CHF/m² (2030), respectively. For frame-improved windows, however, a much more pronounced cost decline is assumed for the first decade to come, viz. 2.5%/a for the window including installation and more than 3%/a for the production cost (without installation).

Figure 12 Estimated costs for windows and various glazing qualities, single glazing (various U-values), double and triple glazing, 2000-2030




Source: Jakob et al. (2002)

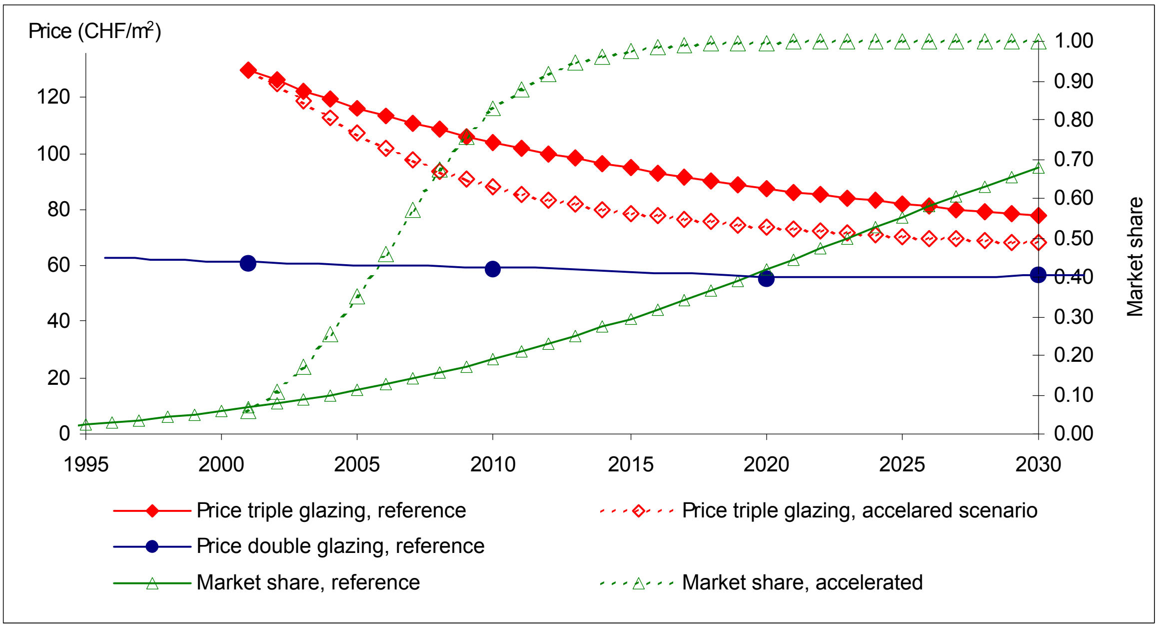
# 5 Energy policy design and evaluation using experience curves

Experience curve analyses can be useful for energy efficiency policy design, making and evaluation, although so far the major focus of the scientific community has been primarily on energy conversion technologies, and especially such based on renewable energy sources (e.g. Isoard and Soria 2001; Menanteau 2000; Neij 1997, among others). In what follows, we will first illustrate with the help of a simple simulation model how an accelerated market penetration of triple glazing may lead to a faster cost decrease (section 5.1). Second, we discuss the optimal timing strategy for the insulation of new and existing building envelopes (section 5.2).

## 5.1 Techno-economic dynamics in an accelerated market diffusion scenario

Figure 13 shows the price trajectories for double and triple glazing under the assumption of different market diffusion paths (measured in market share percentages). For the reference scenario a diffusion curve has been fitted to the historical development of the market share for triple glazing (coated, inert-gas-filled, see Table 6) and the diffusion curve fitted (employing the Standard Bass Model (Bass, 1969; with p = 0.1, q = 0.0035) has been extrapolated to 2030 leading to a relatively slow market share increase (from 7% in 2001 to 19% in 2010 to 42% in 2020). Appling a progress ratio of 0.9 this leads to a price decrease from 130 CHF/m² in 2001 to 104 CHF/m² (-20%) in 2010 and to 88 CHF/m² (-33%) in 2020. As can be seen from Figure 13, an accelerated introduction of triple glazing (dashed line), leading to more than 80% market share in 2010, would result in a more dynamic cost decrease (applying the same progress ratio): in 2010 the cost would drop to 68% of the 2001 price in 2010 and to 57% in 2020. Thus the add-on cost and the marginal cost of energy efficiency (as compared to double glazing) would almost be halved in 2015.

Figure 13 Price development paths for different assumptions on market shares for triple glazed windows, 1995-2030 (simulation)




Source: adopted from Jakob et al. (2002)

It is even imaginable that in the long run the prices for double glazing rise again as the significance of mass production advantages fade. This is the case in Sweden at the moment where double-glazed windows are currently more expensive than triple-glazed ones (sic!).

### 5.2 Optimal timing strategy for building envelope refurbishments within a dynamic techno-economic framework

Even if prices of investments in energy efficiency measures (energy conservation measures) could drop substantially in the future this should not lead to the conclusion that the best strategy for investors is 'wait and see'. Particularly, the following cases can be distinguished:

- Choice of energy quality of the building envelope for new buildings and for energy-related building renewal: if 'only' today's average efficiency standards are applied, the building owner is exposed to the risk of energy price increases, especially compared to investments in appliances and end-use technologies that have a much shorter life time. Indeed, windows, and even more façades, walls and floors have lifetimes of several decades and price increases during this kind of time horizons are quite probable (cf. Jochem and Jakob, 2002). In addition subsequent improvements of building envelopes that comply with today's efficiency standards cause very high marginal costs of energy conservation (as shown in Table 8). Total façade costs including insulation are today at around 120 CHF for 12 cm insulation and 130 CHF/m² (best case) to 170 CHF/m² (average) for 25 cm to 30 cm, respectively. If 12 cm are applied today and further 12 cm are applied in the future (and presuming that the energy prices are higher in 30 years than they are today), the total costs are roughly doubled (minus future cost decreases and minus some value added for the façade's renewal). Even if the future investment is discounted, the present value of the total cost is much higher. Furthermore, because of the high marginal costs of roughly 0.5–0.6 CHF/kWh (the second 12 cm have a much lower energy conservation effect, but the investment is almost as high as for the first 12 cm, see Table 8) no investor would invest into further improvement. The costs for the foregone option are thus quite high when investing today, but only at a rather low level.
- When deciding whether or not to add insulation to formerly non-insulated buildings there is a second kind of lost opportunity. If a façade or a roof is renewed (coating, painting, tile replacement) and no insulation is added, at the same time an opportunity for energy improvements is foregone typically for between 25–30 years (time period façades are normally repaired and repainted) up to 40–50 years (time horizon for tile replacement). However, contrary to the case mentioned above, after this time there is a second chance to invest in energy improvement and the marginal cost of energy conservation in doing will still be quite low. This is even true if the energy improvement is made before the end of the lifetime of the façade painting because the investment opportunity (real option) 'lost' is only a prorated fraction of 30 CHF/m² to 40 CHF/m². This might be another reason why many of the building owners prefer to just maintain the building and to wait with more capital-intensive investments in energy efficiency improvements (needless to say that there are many other reasons for such wait-and-see behaviour).

Table 8 U-values and total and marginal costs of wall insulation improvements implemented today and in 25-30 years from now (stylised)

| | | U-value ($W/m^2K$) | Cost ($CHF/m^2$) | marginal cost ($CHF/kWh_{NE}$) |
|---|---|---|---|---|
| Reference | Insulation 12 cm | 0.28 | 120 | |
| Improved today | Insulation directly to 24 cm | 0.18 | 140 – 160 | |
| | Difference relative to reference | -0.10 | 20 – 40 | 0.12 – 0.23 |
| Improved in 25-30 years | Subsequently from 12 cm to 24 cm | 0.18 | 100 – 115 | |
| | Difference relative to reference | -0.10 | 100 – 115 | 0.56 – 0.66 |

Source: own illustration

Note: costs for future improvements are not discounted

# 6 Conclusions and policy recommendations

In this paper we have discussed the usefulness of experience curve analysis for energy efficiency policy design and evaluation for the building envelope. In particular, by using research results from an extensive recent study for Switzerland, we have illustrated important issues and complexities to be considered in this field of research, without which there is some danger that the cost efficiency of measures tends to be underestimated. At the moment we are not aware of any other attempts to do such kind of analysis in the field and way presented here.

The analysis of some historical trends over the last thirty years has revealed that techno-economic progress has been driven mainly by: (a) building codes and standards; (b) energy price signals; (c) environmental concerns; and (d) the promotion of labels and standards. Starting from the early 1980s and in line with technological progress public authorities in cooperation with private associations have pushed building standards that were gradually adopted by policy-makers and, and eventually incorporated into jurisdiction as legally binding standards (diffusion process among the cantons). In this respect, fiscal incentives played a minor role in Switzerland compared to command-and-control measures.

Expected future policy-related trends important for improving the energy-efficiency of building envelopes comprise the promotion of labels (e.g. MINERGIE), GHG mitigation targets (such as under those contained in the Swiss $CO_2$ Act) and related policy measures (e.g. imposition of a $CO_2$ levy) and other policies (such as export, innovation, social, environmental, etc.). Despite of the clearly demonstrated merits of codes and standards experts expect for the next future that labels would predominate over a further tightening of codes and standards. From the market side an elderly population and more value-oriented financing policies will lead to an increasing discrimination of less energy-efficient buildings. Finally, at the technological frontier, pre-fabricated components with a high potential for the exploitation of economies of scale and learning both on the manufacturing and installation side, will increasingly dominate the building market.

Furthermore we state that the higher the anticipated fuel prices and the more explicit various net ancillary and co-benefits (e.g. such as improved protection from outdoor noise and comfort level increases for the private owner or tenant, or avoided pollutant and greenhouse gas emissions or health costs for the public sector) are taken into account, the larger is the share of cost-efficient 'no regret' measures that can be adopted to improve the energy efficiency of the building envelope.

The paper demonstrates that experience curve analyses are also feasible in the area of energy efficiency measures in general, and such that are applied to reduce the energy demand of buildings, albeit with some caveats that arise mainly from the interrelation between costs and energy efficiency performance that makes the tracing of cost over cumulative output non-trivial. Our empirical analysis yields technical progress factors for wall insulation of around 3% per annum and 3.3% for windows, based on data that cover the past thirty years. We find average price decreases of 0.6% since 1985 for façades, and 25% over the last 30 years for windows. For the time period 1985–2001 we found progress ratios for wall insulation of between 0.8–0.85 and for double-glazed coated windows in the range of between 0.83–0.88.

From the preliminary experience curve analyses undertaken so far, we can derive the following tentative policy design recommendations:

- The imposition and effective control of building standards and their periodic revision helps to ratchet down energy requirements of buildings and fosters standardisation of building components, which itself can promote economies of scale effects that accelerate the diffusion of building insulation measures;
- Voluntary standards, such as the Swiss MINERGIE standard or the German passive energy house standard, can significantly promote the standardisation of components and processes, and thus lead to experience curve gains;
- It seems preferable to promote substantial energy efficiency improvements, as due to the transaction costs involved (e.g. contracting, scaffolding, installation transport) multi-stage measures spread over time tend to be significantly more costly than single-stage measures;
- Building codes for energy performance should not be overly ambitious in order to minimise shirking and to maximise its rate of adoption and excel;
- The communication of the energy costs of buildings to the tenants is an important incentive measure to steer the housing demand also towards more energy-efficient building envelopes;
- Apart from the fuel cost savings that can be achieved by such energy efficiency measures, it is of paramount importance to also consider net co- and ancillary benefits, as these can be of a similar magnitude and thus greatly influence the decision process in favour of energy efficiency improvements;

Overall, the promotion of the virtuous cycle 'standard – innovation – diffusion – cost reductions', the expected spill-over effect from building performance standards for new buildings to refurbishments of existing building envelopes, and the explicit accounting for net benefits are good starting points for successful and innovative policy designs and measures that also keep an eye on experience curve developments and hence on optimal timing.

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