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Building Energy Efficiency

Policy, learning and technology change

Bernadett Kiss

Doctoral Dissertation
June 2013



LUND
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The title of the picture on the front cover is “Out now!” The original photo was taken by Bernadett Kiss in the sustainable city area of the Western Harbour, in Malmö (Sweden) in April 2013. The final cover picture was designed by Lars Strupeit. “Out now!” (presumably) illustrates the author’s wish to further spread the word on *building energy efficiency* among practitioners; however, other interpretations are also possible.

*When you build a house, every brick counts.
When you build character, every thought counts.*

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Preface

This thesis research was performed at the International Institute for Industrial Environmental Economics (IIIEE) at Lund University. The interdisciplinary study presented in this thesis combines insights from the fields of energy, technology, economics, sociology, public policy, and innovation studies. It is directed to the assessment of the role of policy packages in the development of energy efficient end-use building technologies and their emerging markets to ultimately contribute to tackling global energy challenges. The focus is set on (policy) learning as one of the cornerstones of (technology) change. Two research projects framed the objectives and scope of the research. The first project on “Policy instruments for energy efficient buildings” (2008-2010) was funded by Cerbof (Centre for Energy and Resource Efficiency in the Built Environment) research and innovation programme of the Swedish Energy Agency and Svenska Hus AB. The second project “Policy instruments for innovation of energy efficient retrofit measures in existing buildings”, as a part of a larger European project “Integrated strategies and policy instruments for retrofitting buildings to reduce primary energy use and GHG emissions” (INSPIRE) was funded by the Swedish Research Council Formas (2010-2012) and Svenska Hus AB. The thesis includes five papers, two articles published in and two articles submitted to scientific journals, as well as one chapter published in a peer-reviewed book. The institutional and/or financial support of the above-listed organizations is gratefully acknowledged.

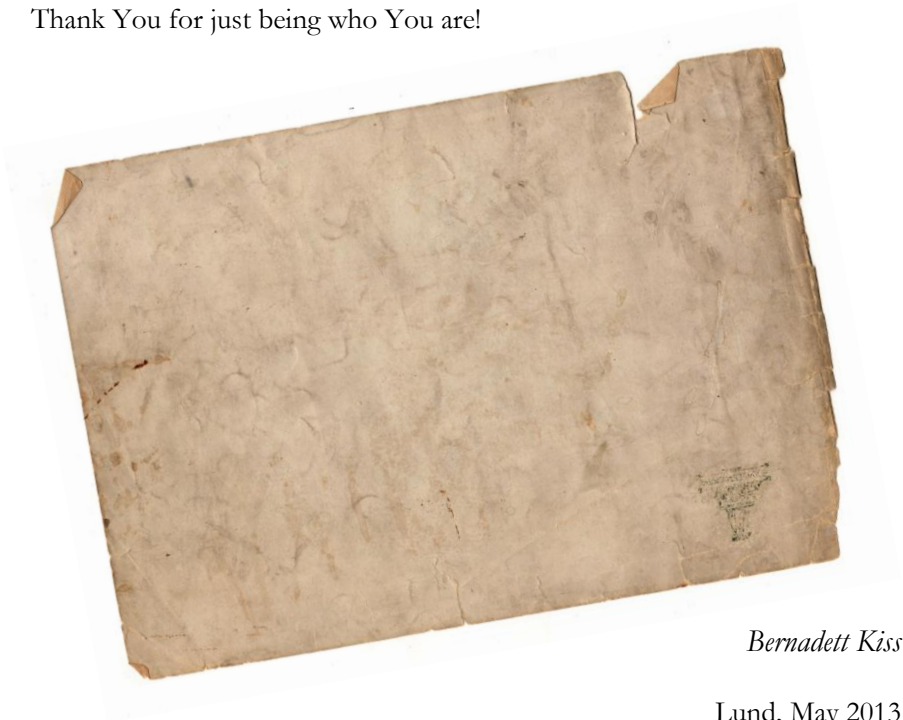
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*"Things do not change, we change."*¹

... and for the change I went through over the PhD years, I would like to express my gratitude for the support and guidance I received from my supervisor, Lena Neij and all my colleagues at IIIIEE. I would also like to gratefully acknowledge colleagues, project partners and organizations beyond the institute whom I have worked with and learnt from over these years. My appreciation also goes to interviewees kindly devoting time, attention and interest to this research.

The printer ink would not be enough to tell all the experience I have been through during this journey; similarly, these pages would not suffice to acknowledge all of you who have stood by me over the past five years. You, who is reading this text, You know exactly how much You matter to me.

Thank You for just being who You are!



Bernadett Kiss

Lund, May 2013

¹ Quote from Henry David Thoreau's (1817-1862) writing, Walden (1854).

Abstract

Experience shows that energy efficiency improvements are the most cost-effective path to meeting global energy challenges. To promote energy efficiency, various policy instruments have been in place since the 1970s. Nevertheless, energy efficiency improvements still lag behind their potential in the building sector, which indicates that there is a lack of knowledge about the performance of policies. To further encourage energy efficiency in buildings, there is a need for 'policy learning' to gain knowledge and experience about policies and their performance.

This doctoral thesis analyses the role of policy instruments and policy packages in the development of energy efficient end-use building technologies and their emerging markets. Technologies include windows, insulation, heat pumps and passive houses. By using the lenses of innovation theory, the concept of learning, and transaction cost economics, this work analyses the outcome of various policy packages, the development of technologies and markets, and policies influencing such development. The research identifies key policy instruments for technology change.

The results show that technology change requires timely, long-term and flexible policy support. This involves diverse policy packages, rather than single policy instruments, designed to support technology development and their emerging markets. The research also highlights the importance of policy support for learning processes in the innovation system and as a determinant of technology change. Building codes, technology procurement and voluntary standards were found to be essential drivers for introducing energy efficient technologies to the market. Beside regulatory and voluntary building standards, testing facilities and networking activities have been identified as key drivers for technology change. Transaction costs, on the other hand, can significantly hinder energy efficiency improvements. Transaction costs of single technologies implemented in passive house renovations can be 200% higher than the transaction costs of conventional technologies. These costs, however, can be reduced.

New approaches to transaction cost reduction and flexible, long-term, policy packages have resulted in more energy efficient windows, improved insulation, widespread use of high quality ground-source heat pumps and growing demand for the application of passive technologies and the passive house concept. In Sweden, for example, the thermal performance of the best available windows has improved more than two-fold in the past forty

years. In the same period, the market share of energy efficient windows increased from 20% to 80%. Another example of successful policy interventions is the emergence of markets for ground-source heat pumps in Sweden and Switzerland. Since the mid-1990s, the efficiency of ground-source heat pumps has improved by 13-36%, annual sales have increased around 20-30% and costs decreased between 50% and 80%, in Sweden and Switzerland, respectively. As the case of a Swedish passive house-oriented renovation shows new approaches to promote learning, e.g. enhanced organizational awareness-raising and new forms of collaboration and information platforms, ultimately result in significant cost reductions at different actors' stake.

This thesis delivers important inputs to the field of policy learning that can be used to enhance, reshape and improve future policies for the development and diffusion of building-sector energy efficiency technologies. Enhanced policy learning, in turn, will help overcome barriers to energy efficiency to support innovation and facilitate technology change for sustainable energy use.

List of publications

This thesis is based on the following papers, which will be referred to by their Roman numbers:

- Paper I:** Kiss, B. & Neij, L. (2011). The importance of learning when supporting emergent technologies for energy efficiency – A case study on policy intervention for learning for the development of energy efficient windows in Sweden. *Energy Policy* 39, p 6514–6524.
- Paper II:** Kiss, B., Gonzalez, C. & Neij, L. (2012). The importance of learning in supporting energy efficiency technologies – A Case Study on Policy Intervention for Improved Insulation in Germany, the UK and Sweden. Article in press. *Journal of Cleaner Production*. Available online since 24 December 2012.
- Paper III:** Kiss, B. (2012). Experience in policy intervention for energy efficient windows – in Germany, Sweden and the United Kingdom. *Submitted*.
- Paper IV:** Kiss, B., Neij, L. & M. Jakob (2012). Heat Pumps: A Comparative Assessment of Innovation and Diffusion Policies in Sweden and Switzerland. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.
- Paper V:** Kiss, B. (2013). Exploring transaction costs of passive house-oriented renovations. *Submitted*.

**Other publications by the author and research colleagues,
which are of relevance to this thesis:**

Kiss, B., Neij, L. & Jakob, M. (2008). *Market transformation for energy efficiency – case study of the introduction and diffusion of heat pumps in Sweden and Switzerland*. Paper presented at the DIME International Conference on Innovation, Sustainability and Policy, Bordeaux, France. 11-13 September, 2008.

Kiss, B. (2009). *Development of energy efficient windows – case study of the introduction and diffusion of energy efficient windows in Sweden*. Proceedings of the Scientific Conference on Energy and IT at Älvsjö fair, Stockholm. March 11-12, 2009 in connection with “Energitinget 2009”. Västerås: Mälardalen University.

Kiss, B., McCormick, K., Neij, L. & Mundaca, L. (2010). *Policy Instruments for Energy Efficiency in Buildings: Experiences and Lessons from the Nordic Countries*. Proceedings of the International Energy Program Evaluation Conference, Paris, France. 9-10 June, 2010.

Kiss, B., Gonzalez, C. & Neij, L. (2010). *The importance of learning in supporting energy efficiency technologies – A Case Study on Policy Intervention for Improved Insulation in Germany, the UK and Sweden*. Proceedings of ERSCP-EMSU Conference in Delft, The Netherlands. 25-29 October, 2010.

Kiss, B. & Neij, L. (2010). *Policy instruments for efficient energy use in buildings*. Cerbof Report, project number 36. Online available:
http://www.cerbof.se/documents/Projekt/Rapporter/CERBOF_proj_36_Slutrapport.pdf

Novikova, A., Amecke, H., Neuhoff, K., Stelmakh, K., Kiss, B., Rohde, C., Dunkelberg, E., Weiß, J., Matschoss, K. & Darby, S. (2011). *Information tools for energy demand reduction in existing residential buildings*. Report of Climate Policy Initiative. Published 27 June 2011. Online available: <http://climatepolicyinitiative.org/wp-content/uploads/2011/12/Information-Tools-for-Energy-Demand-Reduction.pdf>

Kiss, B. & Mundaca, L. (2013). Transaction costs in energy efficiency in buildings – an overview. *International Association for Energy Economics – IAEE Energy Forum*, Volume 22, Second Quarter 2013.

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CHAPTER ONE

“Doing better and achieving more with less”

1. Introduction

Steadily increasing energy use due to our resource-intensive production and consumption patterns, coupled with heightened environmental and social impacts, puts forward the need for more sustainable approaches and policies to address these problems. In this context, energy efficiency – a central approach to tackling global energy challenges, and government policies promoting energy efficiency, are the foci of this thesis. Despite the growing number of policies applied to enhance energy efficiency since the 1970s, continuously growing energy use indicates their effects may be limited; our current knowledge about their overall performance is insufficient. In order to gain more knowledge and experience, the need for more policy learning², including policy evaluation and empirical evidence on past successes and failures, has been repeatedly accentuated in the energy field.

1.1 Background

In better understanding energy efficiency – its importance, the barriers to it and various means to overcome them, the role of policy learning and technology change cannot be underestimated (Mytelka & Smith, 2002). Technology change, in terms of the development and diffusion of energy efficient technologies, and policy learning, in terms of the role of policies in this process, are under the analytical lenses of this thesis. The building sector is used as a case study to understand the challenges of energy efficiency policies in the context of technology change in a selection of European countries.

² ‘Policy learning’ is further elaborated in Chapter 2.

1.1.1 Why energy efficiency matters?

Human *energy consumption* has grown steadily since the industrial revolution, on average at 2% per year (GEA, 2012). Energy is one of our most important resources to power life, by enabling heating, cooling, lighting, mobility and communication. However, besides improving our living conditions in many ways, the extensive and inefficient use of energy has a negative impact on our environment and society. Among others, it causes increased indoor and outdoor air pollution, green house gas emissions and (human) health problems, as well as high dependence of some regions on others in terms of energy supply. If present trends continue, the global energy demand, along with greenhouse gas emissions, is expected to rise by more than one-third over the next twenty years (GEA, 2012; IEA, 2012). Ensuring sustainability in all aspects of economic, environmental and social development while respecting the ecological carrying capacity of the earth requires more efficient resource utilization. To address these challenges, there are various approaches and roadmaps, which on different levels advocate resource and energy efficiency along with the reduction of environmental impacts originated from the production and consumption of goods and services throughout their life-cycles (EC, 2011b; UNEP, 2012)³. To overcome energy challenges, in particular, there are two key approaches: renewable energy⁴ and energy efficiency⁵. In this thesis, energy efficiency is in the focus.

Experience shows that *energy efficiency* improvements provide the most cost-effective options to meet energy challenges; energy efficiency also has co-benefits, such as increased comfort, better health conditions, cost savings, increased energy security, job creation and diverse business opportunities (GEA, 2012). In order to avoid lock-in effects, energy efficiency improvements, especially end-use energy efficiency, should be immediate

³ In this context, resources include inputs into our economy, such as metals, minerals, fuels, fish, timber, water, soil, clean air, biomass, biodiversity and land. The life-cycle perspective means using the resources – from raw material extraction through manufacturing to final use and disposal – with the least impact on other resources (EC, 2011b).

⁴ Renewable energy sources, including biomass, geothermal, hydro, ocean, solar and wind are abundant; we face however a technology challenge to transform them into usable fuels.

⁵ Energy efficiency is understood here as a ratio of energy output to energy input. Energy efficiency improvements refer to using less energy to provide the same service (e.g. heating) or level of activity; the reduction of energy use can be achieved by technological and organizational changes (WEC, 2004).

and inclusive in all sectors. For the implementation of immediate and inclusive actions, both non-technology and technology drivers are required. These include approaches of both public and private actors, nonetheless, government policies inducing changes in technology and actors' behaviour.

1.1.2 Energy efficiency and buildings

Energy efficiency improvements and immediate actions are critical in the building sector, in the existing as well as in the future building stock. The building sector accounts for approximately 31% of the global final energy use and 33% of energy-related CO₂ emissions (Ürge-Vorsatz et al., 2012). Most scenarios show that there is a huge potential to improve building energy performance, and consequently, reduce CO₂ emissions (GEA, 2012; IEA, 2012; McKinsey, 2009). The GEA-Efficiency Pathways⁶ show, for instance, that by using state-of-the-art solutions and technologies in the building sector, a 46% decrease of global final heating and cooling energy use can be achieved between 2005 and 2050; this also includes monetized and non-monetized co-benefits. On a global scale, it is estimated that efficient building technologies can deliver a 30% cost-effective greenhouse gas emission reduction by 2020 (Levine et al., 2007). In the EU, the residential sector can achieve 18-19% cost-effective energy saving potential by 2020 (EC, 2007)⁷. The lack of immediate policy action and state-of-the-art solutions, however, can create a lock-in effect for the following decades and a 33% increase in global energy use in buildings (GEA, 2012).

The building envelope, heating and cooling technologies and energy efficient building concepts play a key role in achieving technically and economically feasible energy efficiency potentials, thus enhancing energy efficiency. Building envelope technologies are technical measures, applied between outdoor and indoor environments, and include high-efficiency building insulation, glazing optimisation and air-tightness maximisation. Applying these building envelope technologies in combination with optimized heating (or cooling)

⁶ GEA-Efficiency Pathways refer to the scenarios developed in the framework of the Global Energy Assessment report (2012).

⁷ In this context, cost-effective energy saving potential is understood as a techno-economic potential, which can be achieved with the best available technologies, which are economically feasible on a national level (EC, 2009). Technical energy saving potential can be achieved by best available technologies, without considering cost and price limitations. Technological potential is estimated to reach up to 29% in the EU (ibid.). For more details on types of potentials for energy efficiency improvement see Jochem, et al. (2000).

technologies as system solutions results in energy efficient buildings. Energy efficiency improvements in the building envelope can reduce the indoor heating demand by a factor of two to four, and up to a factor of eight if other measures, including the optimization of the heating system, are included (Demirbilek, Yalciner, Inanici, Ecevit, & Demirbilek, 2000; Hamada, Nakamura, Ochifuji, Yokoyama, & Nagano, 2003; R. Hastings, 2004; Levine, et al., 2007; Ries, Jenkins, & Wise, 2009; Ürge-Vorsatz, Harvey, Mirasgedis, & Levine, 2007). High performance building retrofits have already demonstrated the ability to deliver a 70-92% heating energy saving potential and new buildings have already been designed and built with high energy performance, e.g. passive houses, zero-energy buildings and plus-energy buildings⁸ (Ürge-Vorsatz, et al., 2012).

1.1.3 Barriers to energy efficiency in buildings

Despite many good examples, *the implementation of energy efficient technologies and concepts is still not a common practice*; this is due to a number of barriers. Barriers to energy efficiency in the building sector include, for example, imperfect information and lack of knowledge. Some barriers are more specifically related to the introduction and development of (new) energy efficient technologies as uncertainty and risk, limited access to technologies, split incentives, high upfront investment costs, transaction costs and limited access to capital (Levine, et al., 2007). Some of these barriers are also defined as market failures, i.e. flaws of market operation not allowing optimal allocation of goods and services, and often hindering cost-effective actions (Levine, et al., 2007; Sutherland, 1991)⁹. Despite the academic debate on to what extent certain barriers should be addressed by policies, the need for policy support for more efficient energy use in buildings and in relation to the introduction and diffusion of energy efficient technologies has been repeatedly accentuated (Levine, et al., 2007).

⁸ While definitions of these terms can vary, the main principle of a zero-energy building is that it produces enough energy on-site to meet its own needs on an annual basis, and a plus-energy building produces annually more than its own energy demand. For the definition of passive house, see Chapter 1.4.1.

⁹ Market failures became the focus of an academic debate in the 1980s in contrast to theoretically perfect markets of neoclassical economics. The main issues of the debate include the identification of market failures hindering cost-effective actions and the application of policy intervention to address these failures.

1.1.4 Policies for energy efficiency in the building sector

Various policy instruments have been applied in different European countries on a national level since the 1970s to support more efficient energy use in buildings. Since the 2000s, building-related energy challenges, including energy savings are of a main concern on the European level, too.

Policy instruments applied for energy efficiency in new buildings have included regulatory, economic, and informative instruments, as well as voluntary approaches (BPIE, 2011; GEA, 2012). Building codes, minimum energy performance standards, technology standards and energy certificates have been the most commonly applied regulatory instruments in European buildings. Building codes have often been coupled with subsidies, soft loans, and tax allowances and in some countries with awareness-raising through energy labelling and energy advice centres. In the past two decades, energy efficiency has been increasingly promoted through voluntary approaches, such as the passive house standard, energy efficiency commitment schemes and advocacy coalitions.

Energy efficiency in buildings has received increasing attention at the EU level in the past decade. The first *Energy Performance of Buildings Directive* (EPBD, Directive 2002/91/EC) was introduced in 2002 and required Member States to set minimum energy performance requirements of new and existing buildings. As of 2020, according to the recast of the EPBD (Directive 2010/31/EU), new buildings and major renovations shall be ‘nearly zero-energy buildings’¹⁰ on a cost-optimal level¹¹. The EPBD is a key component of the European Union’s Energy Efficiency Action Plan to achieve a 20% greenhouse gas emissions reduction, a 20% increase in the share of renewable energy and a 20% improvement in energy efficiency

¹⁰ ‘*Nearly zero-energy buildings*’ are defined by the EPBD as buildings with very high energy performance, where only a small amount of energy is required to run these buildings and to a significant extent this energy should be generated from renewable sources, preferably produced on-site or nearby. This definition leads to further discussions and specifications on terms, such as ‘energy performance’, ‘nearly zero’, ‘very low’ or ‘produced ... nearby’; this discussion is beyond the scope of this thesis.

¹¹ ‘*Cost-optimal level*’ is understood here as minimised lifecycle cost (including investment costs, maintenance and operating costs, energy costs, earnings from energy produced and disposal costs) based on global cost approach (for the detailed methodology, see EC (2012)). In addition, according to the EPBD, building regulations shall also include energy performance requirements for retrofitted or replaced building elements (roof, wall, etc.) if technically, functionally and economically feasible.

(EC, 2011a). In this context, for instance, the passive house standard – as a voluntary approach and a technical measure, i.e. the combination of energy efficient building technologies – is shown to be a technically feasible and a cost-effective solution to achieve these ambitious EU targets (Ürge-Vorsatz, Harvey, et al., 2007; Ürge-Vorsatz, Koepfel, & Mirasgedis, 2007).

1.2 Problem definition

As described above, the relevance of energy efficiency to the building sector is high, the measures are technologically feasible and cost-effective, and various policy instruments have been in place to support energy efficiency since the 1970s. Despite this, energy efficiency improvements in the building sector still lag behind their potential, which suggests the under-performance of the past decades' energy efficiency policies. In general, there is a *lack of knowledge on the performance of policies* and the occurrence of 'mal-performance', for instance, whether it is related to the design, formulation, targets, and implementation of policies, or to the lack of policy improvement and comprehensiveness. In particular, there is a lack of knowledge about their role in the introduction and diffusion of (new) energy efficient technologies (Novikova, 2010; Ürge-Vorsatz, et al., 2012; Ürge-Vorsatz, Koepfel, et al., 2007). In this thesis, it is argued that there is a need for policy learning to gain more knowledge and experience about changes and processes shaping policy issues, including policy performance, to further enforce energy efficiency in buildings.

In order to address this knowledge gap about policy performance, a few goal- and/or achievement-oriented policy evaluations have been carried out in the past decade, focusing on the impacts of policies, while *much less attention was given to policy outcomes*¹² (Harmelink, Nilsson, & Harmsen, 2008; Neij, 2001; Neij & Åstrand, 2006). Evaluating impacts, e.g. energy savings and emission reductions, is important and provides substantial information on results, but very limited insights into other policy outcomes, i.e. processes, changes, market responses, actors' behaviour and learning (Brekke & Johansson-Stenman, 2008; Jochem, et al., 2000; Scricciu, Barker, & Ackerman, 2013). Evaluating outcomes, processes and changes requires new approaches and broader perspectives. Policy outcomes are important

¹² According to the reviewed literature, outcome is targeted actors' response to the policy instrument(s) and impact (can be called final outcome) is a societal and/or environmental change generated by outcomes (e.g. energy use, CO₂ emissions, health problems) (e.g. Hildén et al., 2002; Vreuls, 2005). Outcomes are further elaborated in Chapter 2.

inputs for policy learning to improve policy feedback, policy design, implementation, assessment and evaluation and consequently to overcome barriers to energy efficiency.

In this thesis, it is argued that there is a need for more policy learning, and in particular for policy outcome assessment both in terms of new conceptual system-oriented approaches and empirical case studies on the introduction and diffusion of technologies; such research will be an essential input into future energy policies to enhance energy efficiency and achieve ambitious energy savings targets in the building sector.

1.3 Objective of the research

The overall objective of the research is to contribute to the knowledge base of policy learning and technology change, which in turn can enhance, reshape and improve future policies for improved energy efficiency in the building sector. The research aims to achieve the overall objective by three means:

First, this research aims *to explore and apply approaches novel to the field* of policy evaluation for energy efficient buildings. The focus is on the development of energy efficient end-use building technologies and their emerging markets.

Second, this research aims to investigate the performance of policy packages in the actual development of energy efficient end-use building technologies and their emerging markets. More specifically, the research aims *to assess the outcomes of various policy packages* applied in terms of technology development, market development (i.e. technology cost development, market structure, market actors and networks), and learning processes in the innovation system¹³ (see Table 4-1).

Third, based on the policy outcome assessment, this research aims *to identify key factors influencing the performance of policy packages* for more energy efficiency in buildings.

¹³ NB: The terms 'policy learning' (hereafter 'policy learning') and 'learning processes in the innovation system' (hereafter 'learning') refer to two different learning processes and are discussed in detail in Chapter 2.

The findings of this research will be important inputs for policy learning for energy efficiency, innovation and technology change. The intended methodological contribution of this research is to the knowledge base of energy efficiency policy evaluation approaches, and the intended empirical contribution of this research is to the knowledge base of the characteristics of policy outcomes in relation to policy implementation.

1.4 Research scope

To address the overall research objective and strengthen the coherence and applicability of policy learning and policy evaluation, the papers are scoped by technology, policy, and geography. This research is based on the appended five papers (Papers I-V) and includes a variety of energy efficient technologies in different national policy contexts, assessed in the conceptual framework of innovation system theory (Papers I-IV) and transaction cost theory (Paper V). In addition, the research takes an *ex-post* policy evaluation perspective as a starting point for Papers I-IV, discussing the outcomes of different policy instruments such as technology development, market development, and learning processes in the innovation system. In Paper V the focus is on understanding the source and scale of transaction costs, which is a precondition for advanced and further analysis of future and potential policy design and in particular the outline of policy instruments. Experience gained from these papers is a valuable input for policy learning.

1.4.1 Technologies

The different cases of energy efficient technologies include three individual building technologies and one energy efficient building concept. In terms of technology, the scope is the building envelope and the heating system. Individual building envelope technologies include energy efficient windows and mineral wool insulation; ground-source heat pumps are assessed as an example of energy efficient heating system option for e.g. replacing direct electrical heating systems. The energy efficient building concept discussed in the research is the passive house standard. Table 1-1 provides an overview of the technologies analyzed.

In general, the research has a technology and thus *technology supply focus*, as the structure of production and supply is one of the most important dimensions of the innovation system (Lundvall, 1992). Market structure also provides the context of specific industrial area in which a network of agents

interacting under a particular institutional infrastructure shape the development, diffusion and utilization of technologies (Carlsson & Stankiewicz, 1991). In this research, market structure and development as well as perspectives of the window industry (window manufacturers), the insulation industry (mineral wool producers), the heat pump industry (heat pump manufacturers) and the building industry (building developers) are assessed. In Paper V, the demand side is also touched upon through the perspectives of the building owner and tenants.

Table 1-1. Technology and geography scope

Technology	Relevance	Countries
Energy efficient windows	Windows provide light, view and thermal protection ¹⁴ and take up a minimum of 15% of the building envelope surface; even with reasonably well performing windows, the energy losses through windows can be ten times more per unit area than through walls.	Sweden Germany United Kingdom
Mineral wool insulation materials	Mineral wool insulation is molten stone or glass; its competitive advantages lie in fire safety, noise reduction, and sustainability performance. Heating demand reduction of a factor of two to four can be achieved by higher-efficiency and/or thicker insulation ¹⁵ .	Sweden Germany United Kingdom
Ground-source heat pumps	Heat pumps provide space heating by moving heat from a low temperature heat source (i.e. bedrock) to a higher temperature heat sink (i.e. indoor space) ¹⁶ . They are mostly motor-driven powered by electricity (or gas); in some countries they are considered as energy efficiency measures when replacing direct electrical heating.	Sweden Switzerland
Passive houses	Passive houses have high thermal performance and air tight building envelopes, and efficient heat recovery. The heating energy demand reduction compared to new residential buildings is a factor of 4 to 5, and compared to existing buildings can reach up to a factor of 25. As heat energy is needed only occasionally, the heating system can be kept very simple, e.g. direct electrical heating or a heat pump ¹⁷ . The maximum heating energy demand cannot exceed 15 kWh/m ² /yr.	Sweden

¹⁴ Window functions are described in detail in Bülow-Hübe (2001).

¹⁵ The energy efficiency of windows and insulation is measured by thermal performance, and expressed by U-values. The U-value is the heat flux (Watt) through a surface (m²) at a temperature difference between inside and outside of 1K or 1C. The importance of 'g-value' is acknowledged; however, it is outside the scope of this study. Sources of heating demand reduction: McKinsey (2009); Demirbilek, et al. (2000); Ürge-Vorsatz, et al. (2007).

¹⁶ Ground-source heat pumps transfer heat from water to air or to water; they are installed horizontally (soil), vertically (bedrock) or in water (lake). The performance of heat pumps is measured as the ratio of thermal energy gained to electric power used, called Coefficient of Performance (COP) which is generally in the order of 2.5-5. If a heat pump replaces an alternative heating system, savings will always depend on the configuration of that system, including its conversion efficiency and distribution losses.

¹⁷ Feist, et al. (2005); Hastings (2004); Schnieders & Hermelink (2006).

1.4.2 Policies

The research presented in this thesis focuses on *policy packages*, i.e. policy instruments and the combination of policy instruments, applied to effect technology and market development. Policy packages include both generic policy instruments, such as taxes and information initiatives, and more technology specific policy instruments, such as directed R&D and subsidies. The importance of technology-specific market-oriented policy instruments has been repeatedly accentuated in the context of climate change (see e.g. Azar & Sandén, 2011; Mansikkasalo & Söderholm, 2012; Sandén & Azar, 2005). Policy instruments are of a regulatory, economic, informative and/or voluntary nature (Chapter 2 provides further definitions on policy instruments). In addition, great attention is given to the national context.

In this research, building codes and minimum energy performance standards are the focus of assessment among regulatory instruments. Subsidies, soft loans, tax allowances and technology procurement are considered out of the group economic instruments; and energy labelling, energy advice centres and educational programmes are some of the most important informative instruments, all of which are assessed here. In terms of voluntary approaches, the passive house standard, energy efficiency commitment schemes and networks fall under closer investigation.

1.4.3 Countries and markets

In order to address the overall objective of policy learning, different European countries are chosen to assess the development and diffusion of individual energy efficient end-use building technologies (as summarized in Table 1-1). Due to the long experience in energy efficient buildings, the research funding and the location of the research base (IIIEE), specific attention is given to Sweden. Consequently, all building technologies and the passive houses concept are assessed in the Swedish context. It is done so with a subsidiary aim that Sweden can draw conclusions based on comparing itself with other European countries and policy cultures.

For *energy efficient windows*, in addition to *Sweden, Germany and the United Kingdom* are of interest due to their important role in window technology development and market development. In terms of technology development, the innovations in the plastic window frame and glass industries in Germany and the UK contributed greatly to the introduction of energy efficient windows; while a completely different development path lead to similarly performing windows in Sweden. In addition, Germany and

Sweden are of interest, due to similarly high diffusion rates, but different market structures; and Germany and the UK can be compared based on different diffusion rates under similar market structures.

In terms of *insulation*, in addition to the historically different policy landscapes, *Sweden, Germany and the United Kingdom* are chosen to assess a similar trend in market development, but with a different approach, the sectoral innovation system approach (see Chapter 2). It also seems beneficial from a policy learning perspective to be able to provide insights, not only for national policy learning (i.e. comparing window and insulation technology specific policy instruments in the same countries), but also for cross-country and cross-policy learning.

In terms of *ground-source heat pumps*, *Sweden and Switzerland* are among the few countries in Europe, which provide insightful cases on the development and commercialization of this technology. In these two countries, ground source heat pumps were supported as energy efficiency measures by numerous, but different, policy incentives¹⁸. As a consequence, in 2009, Sweden and Switzerland had the highest number of ground source heat pumps per capita and per land area respectively (EGEC, 2009).

1.4.4 Limitations

This research aims to support policy learning by analyzing and exploring the adequacy of existing approaches in the field of energy efficient buildings to evaluate policy outcomes in terms of technology development, market development, and learning in the innovation system. During this iterative process, the researcher faced some limiting factors described below.

Analyzing technology and market development in case studies is a complex exercise. Therefore, specific descriptors are chosen to describe these developments, which might in turn hinder capturing important factors of these developments. *Technology development* is typically captured by main process and product innovations of technologies and described and quantified by energy performance improvements (expressed in U-values, thickness or kWh/m²/yr), which might limit the further usability of these values and developments to be combined for system approaches, for instance assessing

¹⁸ Austria and Norway also show high diffusion rates, however, due to their different electricity mix, they fall outside the focus of this study.

building system performance or competing and/or alternative energy efficient technologies.

Market development is typically described by the development of market sales, market share, market price, market actors and networks with the starting point of the present market structure. Market sales, market share, and market price information is greatly limited by the availability and quality of data sources. This is relevant to consider in market-oriented evaluation research. In terms of market structure, an important delimitation to remember is that the research focus is on the technology supply side, and thus the analysis does not include market demand considerations, demand-driven approaches and the interaction between technology supply and market demand¹⁹.

In terms of *policies*, only those with the focus of energy efficiency in buildings are considered. The policy scope of further research could be broadened with, for example, policies on property rights and values in order to address cost-optimality issues of future building codes. In addition, more voluntary approaches, such as public-partnership schemes, especially those focusing on financial arrangements, can be of interest, for example to overcome economic barriers of energy efficiency. Although individual policy instruments and their combinations are assessed here, disentangling policy instruments or their individual effect is beyond the scope of this research.

1.5 Thesis outline

The thesis consists of an introduction '*Le Chapeau*' presented in five chapters and five appended papers with contributions from the author (see Table 1-2).

In Chapter 1, the scene is set for the thesis by describing the context (1.1) and the research problem (1.2), defining the research objectives (1.3), setting the boundaries and addressing the limitations (1.4), and by outlining the main content of the thesis (1.5).

¹⁹ It has to be mentioned, however, that by applying parameters, such as technology performance, market sales and market price, the interaction between market supply and demand are partly captured (McNulty, 1968; Porter, 1979, 2008; Schumpeter, 1961).

In Chapter 2, the conceptual framework describes the main considerations the thesis is built upon by defining policies and related issues (2.1), elaborating the importance of policy outcome evaluation in the context of policy learning (2.2). The Chapter introduces two concepts for policy outcome evaluation by depicting innovation system theories, with the focus on sectoral innovation system and learning (2.3) and transaction cost economics (2.4).

In Chapter 3, methodological issues of the research are addressed by describing the scientific positioning of the research (3.1), the research methods chosen for data collection and analysis (3.2) and the measures to ensure reliability and validity (3.3).

In Chapter 4, the main findings and observations are presented paper-by-paper by describing the objectives, approaches applied and results of the papers in the light of the overall research objective, including remarks on the relations between different papers to each other.

In Chapter 5, concluding remarks are formulated with regards to the main research objective (policy learning) in terms of exploring policy evaluation approaches (5.1), the assessment of the actual development of energy efficient end-use building technologies and their emerging markets and the role of policy packages in this (5.2). In addition, key components of policy packages are identified as drivers for technology change (5.3). The Chapter also includes the key contribution to the existing knowledge base (5.4) and suggestions for further research (5.5).

Table 1-2. Appended papers and the author's contribution

Publication	Contribution	
Paper I	<p>Kiss, B. & Neij, L. (2011). The importance of learning when supporting emergent technologies for energy efficiency – A case study on policy intervention for learning for the development of energy efficient windows in Sweden. <i>Energy Policy</i> 39, p 6514–6524.</p>	<p>As first author, the researcher was responsible for the research framework, methodology, conducted data collection and the majority of the analysis and wrote the major part of the article.</p>
Paper II	<p>Kiss, B., Gonzalez, C. & Neij, L. (2012). The importance of learning in supporting energy efficiency technologies – A Case Study on Policy Intervention for Improved Insulation in Germany, the UK and Sweden. Article in press. <i>Journal of Cleaner Production</i>. Available online since 24 December 2012.</p>	<p>As first author, the researcher was responsible for the research framework, methodology, conducted part of the data collection and the majority of the analysis and wrote the major part of the article.</p>
Paper III	<p>Kiss, B. (2012). Experience in policy intervention for energy efficient windows – in Germany, Sweden and the United Kingdom. <i>Submitted</i>.</p>	<p>As the single author, the researcher designed the research framework, conducted all the research and analysis, and wrote the entire article.</p>
Paper IV	<p>Kiss, B., Neij, L. & M. Jakob (2012). Heat Pumps: A Comparative Assessment of Innovation and Diffusion Policies in Sweden and Switzerland. <u>Historical Case Studies of Energy Technology Innovation</u> in: Chapter 24, <u>The Global Energy Assessment</u>, Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.</p>	<p>As first author, the researcher was responsible for the methodology, collected all the data did part of the analysis and wrote parts of the article.</p>
Paper V	<p>Kiss, B. (2013). Exploring transaction costs of passive house-oriented renovations. <i>Submitted</i>.</p>	<p>As the single author, the researcher designed the research framework, conducted all the research and analysis, and wrote the entire article.</p>

CHAPTER TWO

*"Without a theory ...nothing to pass on
except a mass of descriptive material
waiting for a theory, or a fire"*
Ronald Coase (1984)

2. Conceptual Framework

Pursuant to the problematization and the objectives of the research, this Chapter conceptually considers how to advance *policy learning* and how to frame the analysis of *technology change*. In the search for new approaches to track changes in techno-socio-economic systems and to find solutions for today's energy challenges, the evaluation of energy efficiency policy (instruments) is conceptualized in an innovation systems perspective through learning processes and transaction cost analysis embedded in case studies.

To avoid terminological confusion, it is emphasized that there are two types of learning referred to in this thesis. Policy learning is the field to which this research contributes its findings; studying policy learning, however, is out of the scope of this thesis (Section 2.2). Learning processes on the other hand as key drivers for innovations are analysed in detail and applied as a tool to assess the development and diffusion of energy efficient end-use building technologies (Section 2.3.2 and Section 3.2.2).

2.1 Policy and policy instruments (definitions)

Policy definitions are broadly discussed in several streams of literature (e.g. Hill, 1997; Vedung, 1998). Policy, in a broad sense, refers to complex (multiple and multilevel) decisions followed by a program of actions or a set of principles on which the actions are based (Hill, 1997; Kemp & Weehuizen, 2005). The decisions, actions and principles usually represent and allocate certain values (Easton, 1953), and they are adopted by public or private actors (Jefferson, 2000; Owen, 2004). In this research, based on the 'choice approach'²⁰, policies are described as government interventions through different instruments and resources (e.g. organizational, financial or

²⁰ The choice or continuum approach is described in detail in Vedung (1998) and Howlett (1991), respectively.

human), i.e. public policies. Policies, other than public ones, suggest a ‘non-intervention’, where the government leaves the choice for action to private actors, market mechanisms and civil society (Howlett, 1991; Vedung, 1998; Åstrand, 2006)²¹. In addition, Fischer (1995) helped to fine-tune the definition of public policy used in this research, by adding a political perspective to it; according to Fischer’s definition, public policy is a set of actions (or inactions) focusing on issues which are on the political agenda with the intention to resolve them.

Energy efficiency policy, as a part of energy policy, is a complicated subject at the intersection of various disciplines such as technology, economics, sociology, geography and politics (Energy Policy (Ed.), 1973). Historically, energy policy had a strong technology focus and was defined as the implementation and the technology assessment of a country’s energy plan (UN (Ed.), 1991). Furthermore, Johansson and Goldemberg (2002) define energy policy as decisions and actions addressing energy systems, from energy supply (production, conversion, carriers, distribution) to energy demand (consumption). Owen (2004) places energy policy in a sustainability perspective and argues that energy policy involves private and public actors of the economic, environmental, political and social planning of energy supply and utilisation. For the purpose of this research, based on Mundaca (2008), energy efficiency policy refers to principle-based actions carried out by private or public actors with the intention to bring about (or to prevent) change for energy efficiency improvements including its economic, environmental and social implications.

Policies are implemented in the form of *policy instruments* (Fischer, 1995; Vedung, 1998). Policy instruments are defined as basic techniques or tools of (governmental) actors attempting to support or prevent social change by modifying the behaviour of subject groups to achieve policy goals (Carter, 2001). In practice, policy instruments are not isolated, but often share common grounds by being part of a portfolio, scheme, system, programme or policy package (Carter, 2001; Salamon & Lund, 1989). For the purpose of this research, policy instruments for energy efficiency are defined as *governing techniques used by private or public actors to implement energy efficiency policy by changing actors’ behaviour*. In this context, policy instruments are categorized as regulatory, economic, informative and voluntary; the category definitions are based on Vedung (1998) and Mont and Dalhammar (2005). *Regulatory*

²¹ According to the choice approach, voluntary agreements and public-private partnerships are placed in the grey zone somewhere between public and private actions.

(administrative or command-and-control) instruments call for the mandatory fulfilment of certain requirements by targeted actors. *Economic* instruments are defined as financial (dis)incentives to trigger change by providing (new) favourable (or unfavourable) economic conditions for targeted actors. Positive incentives include subsidies, soft loans, tax allowances and technology procurement; negative incentives are taxes, fees and charges. *Informative* instruments aim at providing information or knowledge to targeted actors in order to increase awareness and support informed decision-making to accomplish or prevent social change. *Voluntary* approaches are commitments and actions, beyond legal requirements, undertaken by private actors and/or non-governmental organisations.

2.2 Policy learning

Policy learning is a broad concept and has been defined by several scholars (e.g. Etheredge, 1981; Hecló, 1974; Lindblom & Cohen, 1979; Rose, 1988, 1991; Sabatier, 1987, 1988). Policy learning is built upon theoretical frameworks from different disciplines, integrating cognitive, organizational and political science, combined with empirical findings from innovation studies. All scholars referred to see learning as an *increase in knowledge about the design, implementation, assessment of policies and the resulting feedback on those policies*. However, depending on the disciplinary background, views greatly vary on the subject (who learns), the object (what is learnt) and the impact (of learning)²². Kemp & Weehuizen (2005) refers to policy learning as a *structured and conscious change in thinking about a specific 'policy issue'*; a policy issue is defined as an action and/or a set of principles on which policies are based, including the actors involved in e.g. the formulation of principles and the adoption of policies (Bennett & Howlett, 1992). Policy learning affects both the means (processes) and the ends (goals). According to Hall (1993) policy learning can be encountered on three levels: policy instrument, policy package and policy goal²³. In this research, policy learning is understood as a *process, which reshapes and changes policy issues*, ideally for the better.

²² Bennett & Howlett (1992) discuss approaches to policy learning; Hall (1993) and Pierson (1993) discuss policy learning in relation to policy-making processes and political change.

²³ Three level learning is demonstrated here through a hypothetical example. The policy goal of the government is to increase energy savings in the building sector. In order to achieve this goal policy packages are designed, including policy instruments, such as building codes, tax allowances, and advice centres. Tax allowances for replacing old windows with new energy efficient ones were evaluated. Evaluation results showed that the energy savings goals were

2.2.1 Policy evaluation

Policy evaluations are essential to gain more knowledge about the performance of policies. *Policy evaluation, as an important component of policy learning*, has emerged and been used to assess the performance of energy policies to various extents in the past decade. These evaluations, however, had more focus on the *impact* of policies, in terms of results in e.g. energy savings and emissions reductions (e.g. Gillingham, Newell, & Palmer, 2006; Vreuls, 2005), and less on the *outcomes*, e.g. technology improvement, knowledge development and actors' involvement. To provide insights into technology change – the development and diffusion of energy efficient technologies and the role of actors and networks – the need for policy outcome assessment has been increasingly emphasized (e.g. Kemp, 1997; Neij, 2001). Policy evaluation, in the context of this research, is understood as a “careful assessment of the merit, worth and value of administration, output and outcome of environmental policies, which is intended to play a role in the future, practical action situations”, ‘assessment’ refers to an *ex-post* as well as an *ex-ante* perspective (Mickwitz, 2003; Vedung, 1997)²⁴. Outcomes, in this context, are understood as policy-induced changes in the system; in other words, market responses and/or actors' (re)action to policy instrument(s). The assessment of policy outcomes, in addition to policy impacts, can increase our understanding of policy processes and their relevance, efficiency, legitimacy and implementation²⁵. Policy outcome assessment can also provide insights into social, technical and market related changes and the processes leading to these changes in the system.

In this research, the outcome of policy instruments is assessed in terms of technology development, market development, actors and networks, cost

not reached. As a response, the government might decide to a) redesign the tax allowance (first order learning – about the policy instrument), b) eliminate the tax allowance, introduce subsidies for renewable sources to the policy package and run an awareness raising media campaign (second order learning – about the policy package) and/or c) reconsider and change the policy goal to increased energy efficiency instead of energy savings (third order learning – about the goals).

²⁴ In this research, as in the policy literature, several terms have been used for policy evaluation and related processes, including assessment, analysis, investigation, examination, study, review, etc. (Chen, 1990; Fischer, 1995; Pawson & Tilley, 1997; Rossi, Lipsey, & Freeman, 2004; Scriven, 1991).

²⁵ For more information on policy evaluation criteria, see Bemelmans-Videc, Rist & Vedung (1998), Hildén (2002), Mickwitz (2006) and Mundaca (2008).

development, learning processes and transactions (expressed as transaction costs). *Technology development* is understood as product and process innovations. *Market development* is understood as the diffusion of energy efficient products on the market under certain market supply structures, and changes in product sales, market share, and product price²⁶. Market structure, i.e. the structure of production and supply, is one of the most important dimensions of technology diffusions in the innovation system (Lundvall, 1992) and therefore is included in the assessment (Papers I-IV). Market structures can be described by multiple parameters; the ones applied in this research are described in Paper III. *Actors and networks* are described by (the change of) their relation to the developed technology, to each other and to the system. Networks are understood as a formation of interest groups; the interests investigated here are mainly based on energy efficiency. *Learning*, as an outcome, i.e. a process leading to changes in the system, is discussed in Section 2.3.2. Table 4-1 presents the focus of policy outcome assessment paper-by-paper.

2.3 Innovation system theory and learning

Innovation system theories have been developed and used to various extents to assess the impact of energy policies in the past three decades. The theories of innovation system, which originated in the late 1980s, state that innovations develop in a context, i.e. systems consisting of different system components, which interact with each other (e.g. Freeman, 1987, 1988; Lundvall, 1988, 1992; Nelson, 1994; Nelson & Rosenberg, 1993)²⁷. In these systems, one of the key links among system components is learning (e.g. Arrow, 1962; Rosenberg, 1982).

²⁶ Product price is also referred to as cost development here; in Papers I and IV it also includes cost structure.

²⁷ Since their introduction, theories of innovation systems have been elaborated by many other scholars besides the above-mentioned (e.g. Bergek, Jacobsson, Carisson, Lindmark, & Rickne, 2008; Carlsson, Jacobsson, Holmén, & Rickne, 2002; Carlsson & Stankiewicz, 1995; Edquist, 1997; Jacobsson & Johnsson, 2000). Network theories, such as the actor-network theory (Callon, 1986, 1987) and SCOT, the theory of social construction of technical systems (Bijker, Hughes, & Pinch, 1987) have fed into innovation theories. System-oriented approaches, for the analysis of energy systems, such as the theory of large technical systems (Hughes, 1983, 1987; Kaijser, Mogren, & Steen, 1988) have also contributed to innovation theories to develop.

Lundvall (1988) defines an *innovation system* as “a purposeful set of elements that interact with each other through ubiquitous processes of creation and the diffusion of artefacts and knowledge”. Some scholars define innovations more rigorously restricting them to technologies (e.g. Carlsson & Stankiewicz, 1995; Nelson & Rosenberg, 1993). Others take technological innovation as the core of the analysis, but also consider organizational and institutional innovations (e.g. Edquist, 1997; Lundvall, 1992). The scope of innovation systems can also differ; national innovation systems have been described by e.g. Freeman (1988) and Lundvall (1988, 1992), the regional innovation system perspective have been promoted by Cooke (1996) and the sectoral innovation system approach by Breschi & Malerba (1997). Although definitions vary among scholars, the core idea upon which the concept of innovation system is based remains the same; relying on the existence, interaction and influence of system components which together build and shape the innovation system. System components include actors (e.g. organizations, companies, governmental and non-governmental bodies), artefacts (e.g. technologies, products) and institutions (e.g. legislations, traditions, social norms).

Learning is described as a key component of innovation systems which can take place between any components (Lundvall, 1988, 1992). Freeman (1988) emphasizes the importance of learning in different innovation phases among different actors and argues that “the national system of innovation is [...] a cumulative process of learning by producing, learning by using and learning by interaction of producers and users”. The technology innovation literature highlights knowledge competence and knowledge-competence networks (Bergek, et al., 2008; Carlsson & Jacobsson, 1997; Carlsson & Stankiewicz, 1995; Carlsson & Stankiewicz, 1991; Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007) as key drivers of innovation.

Based on the common features described by Lundvall (1992), *innovation systems are considered as systems characterized by holistic viewpoints, which are composed of actors, networks and institutions and their relationships*, where one of the main process drivers is learning. Technological innovation²⁸ is in the focus of

²⁸ Technology innovation is based on the technical system approach (Hughes, 1983, 1988), where technologies are components of a system and the goal of the system is to expand (Hughes, 1987). System components interact to achieve the system goal. Technology innovation is an evolutionary, path-dependent and open-ended process and this process can greatly differ among countries. Path-dependency is also called exemplar (Kuhn, 1970), dominant design (Abernathy & Utterback, 1978), technological trajectories (Nelson & Winter,

these systems, but the organizational and institutional setting and the interactions among system components also play an important role. As the boundaries of innovation systems are difficult to delineate (Edquist, 2001), in this research, the core elements of the individual innovation systems and the relations among these are selected and defined.

Innovation system theory and the concept of learning in innovation systems provided the conceptual framework for Papers I and II. More specifically the conceptual framework of a sectoral innovation system was applied in Paper II. Papers III and IV also rely on innovation system theory perspectives.

2.3.1 Sectoral Innovation Systems

The conceptual framework of sectoral innovation systems (SIS) has been repeatedly applied to analyze specific technologies, production processes, demand and knowledge bases generated and utilized by systems of firms (Malerba, 2002). The concept was developed by Carlsson & Stankiewicz (1995) based on the arguments that technological systems are specific to technologies and thus require a sectoral rather than a national approach. Breschi & Malerba (1997) focus on systems of firms; whereby firms develop products with the assistance of the sector's technologies and are related to each other through cooperation and/or competition. Malerba (2002) further develops the sectoral innovation approach by drawing key insights from evolutionary theory and the innovation system approach²⁹ identifying the basic components of the system. The sectoral innovation system consists of *products* and *agents*, *interacting* for the development and diffusion of these products. In addition, the system is built on and driven by a *knowledge base*, *technologies*, *inputs* and *demand*. The agents are organizations, i.e. firms (e.g. users, producers, suppliers) and non-firms (e.g. universities, banks, governmental bodies, associations), and individuals (e.g. consumers, entrepreneurs). Agents are characterized by specific competencies, beliefs, objectives and interact through processes of communication, learning, co-operation, and/or competition. These processes of interactions are

1982), technological paradigm (Dosi, 1982), or innovation avenues with technological guideposts (Sahal, 1985) in the literature.

²⁹ 'Sector' is defined based on the traditional concept used in industrial economics; it both refers to firms and non-firms and assesses both market and non-market interactions. The focus is on transformation processes. Sectoral system boundaries are flexible.

influenced by *institutions*, which according to Malerba (2002) include both ‘formal’ rules, laws and standards and ‘informal’ norms, habits and practices.

In this research, the sectoral innovation system framework is applied in Paper II, with the emphasis on the structure of the system and its components. The research assesses the following components: (i) *technologies (products)*, (ii) *actors (agents)*, (iii) *knowledge and learning processes*, (iv) *mechanisms of interaction (networks)*, and (v) *policy instruments (as an element of institutions)*. The sectoral innovation system framework provides a feasible approach to tackle the international nature of the mineral wool insulation market and the national nature of policy frameworks.

2.3.2 Learning in innovation systems

In the literature, learning within the innovation system is acknowledged to be a significant driver of innovation and technology change (e.g. Arrow, 1962; Jensen, Johnson, Lorenz, & Lundvall, 2007; Kamp, Smits, & Andriess, 2004; Lundvall, 1992; Rosenberg, 1982). Learning is a process *by which new or existing knowledge, skills and experience are developed*.

The literature acknowledges *different types of knowledge* in the context of technology development. For instance, based on the taxonomy developed by Dannemand Andersen (1993), knowledge can be (i) embodied or disembodied³⁰, (ii) tacit or formalised³¹, and (iii) R&D-based or experience-based³². Although the classification of different types of knowledge presented here is important, they are applied to limited extent in the papers. For the purpose of studying learning processes in the innovation system, the main focus in this research is on disembodied, formalised, R&D-based and experienced based knowledge.

³⁰ Embodied knowledge can be, for instance, a component of a technology, such as the glass pane in window technologies. Window manufacturers, as users of glass panes, do not have to know how to produce glass, but only how to mount glass panes into the window frame.

³¹ Tacit knowledge refers to that part of individuals’ knowledge, which is not codified. Polanyi (Polanyi, 1958, 1966) emphasizes the difficulties related to the transfer of tacit knowledge and suggests specific environments for tacit knowledge transfer.

³² In addition, Garud’s taxonomy (1997) presents knowledge in different terms: (i) knowing why, (ii) knowing how, and (iii) knowing what. Lundvall (1992) adds to this classification by emphasizing the importance of (iv) knowing who. In addition, Malerba (1992) defines internal and external knowledge, depending on where firms obtain the knowledge.

There are *different ways for knowledge, skills and experience to be acquired and developed*; this happens through processes of learning, also called knowledge creation, knowledge sharing, and knowledge transfer. Learning is a broad concept and various processes of learning have been identified in the innovation literature (e.g. Arrow, 1962; Garud, 1997; Kamp, et al., 2004; Lundvall, 1992; Rosenberg, 1982). For the purpose of this research, based on Kamp, et al. (2004), four learning processes are used to analyse the development and diffusion of energy efficient building technologies in Papers I and II. These are *learning-by-searching*, *learning-by-doing*, *learning-by-using* and *learning-by-interacting* (see a brief summary in Table 2-1). The learning processes and their application in the context of policy evaluation are described in detail in Paper I. The concept of learning is an important component of this research and learning is also tracked in Papers IV and V.

Table 2-1. *Characteristics of learning processes – including examples of actors and outputs*

Learning process	Characteristics	Actors involved (examples)	Potential outputs (examples)
Learning by-searching	A systematic way of acquiring (new) knowledge through R&D or study.	Universities, research organisations, R&D departments of companies.	Publications, reports, articles, patents, R&D resources, prototypes.
Learning by-doing	Routines, practices, trainings – where labour learns through experience in the production phase.	Production and production-related departments of companies.	Production time, magnitude (and quality) of output, testing, training.
Learning by-using	Practice and feed-back based on user-experience.	Technology users and producers – marketing, client relation departments.	Feed-back frequency and content.
Learning by-interacting	Information flows through multiple channels and relationships among multiple actors.	Universities, research institutes, companies, industry associations, suppliers, users, governmental bodies.	Platforms and interfaces of interaction, intermediaries, networks.

2.4 Transaction cost economics

Departing from new institutional economics³³, transactions cost economics assesses *institutional arrangements, processes and interactions through contractual relationships*³⁴. In this context, institutions are understood as “...rules of the game in society ... humanly devised constraints that shape human interaction ... they structure incentives in human exchange, whether political, social, or economic” (North, 1990, pp. 3-4). Institutional arrangements, also called ‘governance structures’, include guidelines and the actors that developed them to mediate economic relationships (Williamson, 1985, 1996). Economic relationships or exchanges of goods or services are transactions. The transaction is the basic unit of analysis in new institutional economics. Transaction cost economics assumes that transactions are typically based on ‘bounded rationality’ (imperfect and asymmetric information), so transaction costs are presumably a part of all economic relationships. New institutional economics assumes that institutional arrangements are chosen to best adapt to certain transactions and can reduce total costs at certain times (Joskow, 2008). Therefore, the characteristics of the transactions and their costs are important to understand.

Transaction costs are costs not directly involved in the production of goods or services, but unavoidable and often unforeseeable costs that emerge from contracting activities essential for the trade of such goods and services (Coase, 1960). In the field of technology change, transaction costs are often referred to as unmeasured costs that prevent the adoption of new technologies. Transaction costs are often understood as *costs occurring ex-ante to the arrangement and implementation of technologies and ex-post in relation to the monitoring and enforcement of contracts* (Matthews, 1986). Transaction costs can impose a critical market barrier by making new technologies (seem) more expensive than conventional ones.

For the purpose of the research presented in this thesis, ‘transaction cost economics’ is used in the broad sense, as a theory that based on Ménard

³³ New institutional economics aims to understand the market effects of decisions and transactions of market actors as well as the influence of institutional frameworks on the behaviour of these actors (Ménard, 2004a; Williamson, 1996).

³⁴ In this context, a contract is described as a purposefully designed agreement and a mutually approved legal commitment between actors to organize and implement transactions (Brousseau & Glachant, 2002).

(2000) aims to provide understanding of transactions, i.e. interactions, induced by the economic performance of firms and markets, between private and public actors and formal and informal institutions. It also considers actors' behaviour, such as human incentives, preferences, perceptions, beliefs and learning (North, 2004). In this research, interactions are analyzed through transactions and transaction costs. Transaction costs, based on Matthews (1986) are here defined as *ex-ante* and *ex-post* costs with regards to the arrangement, monitoring and enforcement of the (contracted) implementation of technologies. Special focus is given to the *nature* (origin) and *scale* (order of magnitude) of transaction costs.

In the energy policy and energy efficiency literature, *multiple sources of transaction costs have been identified* (see Table 2-2). Transaction costs of implementing energy efficiency can arise throughout the life-cycle of projects in the planning, implementation and monitoring phases (Mundaca, Mansoz, Neij, & Timilsina, 2013). The most typical transaction costs related to the introduction and commercialization of energy efficient technologies were found to be searching for information, contract negotiations and monitoring (*idem.*). Some studies have also attempted to provide empirical estimates of the scale of transaction costs in the building sector; these quantification exercises, however, have shown methodological challenges which often result in incomparable figures. Transaction costs were presented, for instance, as a proportion of investment costs, as an absolute cost or as a work load (time) (Björkqvist & Wene, 1993; Easton Consulting, 1999; Mundaca, 2007). In Sweden, transaction costs in the building sector are estimated to be 20% of the investment costs (Ürge-Vorsatz, et al., 2012). More specifically, transaction costs for lighting technologies were estimated to be 10%, for improved cavity wall insulation 30%, and in the range of 20%-40% for energy efficiency measures carried out by energy service companies in the residential sector (Easton Consulting, 1999; Mundaca, 2007). In any case, all estimates of transaction costs are subject to uncertainty due to the performance of the technology, accountability, reliability and accuracy of data sources and the methods of monitoring and quantifying transaction costs.

Table 2-2. Overview of the nature of transaction costs in the energy policy literature

Nature of transaction costs	References (examples)
Administration, registration ³⁵	(Joskow & Marron, 1992; Michaelowa, Stronsik, Eckermann, & Hunt, 2003; Mundaca, 2007)
Approval, certification	(Hein & Blok, 1995; Michaelowa, et al., 2003; Mundaca, 2007)
Contracting, procurement, tendering and awarding	(Bleyl-Androschin, Seefeldt, & Eikmeier, 2009; Mundaca & Neij, 2006)
Decision-making process	(Björkqvist & Wene, 1993; Hein & Blok, 1995)
Enforcement, verification	(Michaelowa, et al., 2003; Mundaca, 2007; Mundaca & Neij, 2006)
Information collection (search)	(Björkqvist & Wene, 1993; Coase, 1937; Hein & Blok, 1995; Michaelowa, et al., 2003; Mundaca, 2007; Mundaca & Neij, 2006; Sanstad & Howarth, 1994; Sathaye & Murtishaw, 2004; Sioshansi, 1991; Stavins, 1995)
Information assessment	(Hein & Blok, 1995; Mundaca, 2007; Mundaca & Neij, 2006; Ostertag, 1999; Sanstad & Howarth, 1994; Sathaye & Murtishaw, 2004)
Information validation	(Kerr & Maré, 1998; Michaelowa, et al., 2003; Mundaca, 2007)
Information application	(Hein & Blok, 1995; Mundaca & Neij, 2006; Sanstad & Howarth, 1994; Sathaye & Murtishaw, 2004)
Information loss	(Kerr & Maré, 1998)
Legal fees	(Finon & Perez, 2007)
Liability risk	(Mundaca, 2007)
Maintenance	(Ostertag, 1999)
Monitoring, quality checks, review	(Bleyl-Androschin, et al., 2009; Hein & Blok, 1995; Michaelowa, et al., 2003; Mundaca, 2007; Stavins, 1995)
Negotiation, third party facilitation, assistance, data reparation	(Bleyl-Androschin, et al., 2009; Kerr & Maré, 1998; Michaelowa, et al., 2003; Mundaca, 2007; Mundaca & Neij, 2006, 2007; Ostertag, 1999; Stavins, 1995)
Persuasion	(Mundaca, 2007)
Project preparation, formulation	(Bleyl-Androschin, et al., 2009)

³⁵ NB: Some scholars argue that administration is not a source of transaction costs (see e.g. Ostertag, 1999)

CHAPTER
THREE

*"We all must face problems,
but it is how you face them
that counts"*

3. Research Methodology

In order to understand the complexity of today's societal problems, researchers need to take understandable ontological and epistemological positions from which problems can be investigated through several perspectives (Hakim, 2000). Policy-oriented research is anchored in multiple disciplines, applying multiple theoretical approaches and concepts, which are often problem-oriented and interdisciplinary³⁶. Such multifaceted complexity requires multiple methods to provide a coherent picture of the topics studied (Majchrzak, 1984; Mickwitz, 2006; Rossi, et al., 2004). While in Chapter 2, the theoretical and conceptual framework applied to pursue the research objectives was described; in this Chapter the methodological choices are explained.

3.1 Scientific research positioning

The scientific positioning of research is framed by research paradigms, i.e. views that link researchers to specific research communities (Denzin & Lincoln, 2005; Kuhn, 1970). Research paradigms can be described by the researcher's ontological, epistemological and methodological position (Guba & Lincoln, 1998). In this sense, ontology refers to the nature of existence, epistemology to the nature of knowledge and methodology to the means and methods applied to research issues in a specific field.

The *ontological* position of this study leans toward a critical realist view, whereby the researcher 'knows' that an external reality exists outside the researcher's reality. The researcher's aim is to understand this external

³⁶ In this context, interdisciplinary research is understood as a type of research carried out by teams or individuals by integrating data, tools, concepts, and/or theories from two or more disciplines to advance understanding and/or to solve problems beyond the scope of a single discipline (CFIR, 2005).

reality. The researcher's reality is, however, filled with values, knowledge and experience and has some influence on the external reality, e.g. when measuring, calculating and presenting it. The external reality manifests itself in specific phenomena, such as resource scarcity, climate change and energy challenges, and as such can be understood and explained. However, due to our imperfect knowledge and restrained comprehension, these phenomena can be comprehended only to a limited extent; so this new understanding feeds in to the researcher's reality.

In terms of its *epistemology*, this research is positioned along the lines of post-positivism and interpretivism. It is post-positivist, because it treats policy-oriented research and specifically policy evaluation as a value-laden process (Fischer, 1995). In this context, the world and changes in the world are socially constructed, and facts and values are not separable (Denzin, 1978; Devine, 2002; Halvorsen, 1992). The research is interpretative, because it focuses on creating knowledge for better understanding of a phenomenon beyond the positivist causal relationship. The knowledge created includes facts and values and considers explanations as interpretations of researchers (Marsh & Furlong, 2002). The ontological and epistemological stances are in line with policy-oriented research, which in general terms aims to create knowledge for understanding and explaining value-laden cause-effect processes for policy improvement, ultimately to bring about changes in the societal and ecological system (Fischer, 1995).

According to Bryman (2004), the research *methodology* is framed by the research objectives, the theoretical perspectives and the ontological and epistemological positions. These considerations also determine the empirical nature of the research and the methods applied (Denzin, 1978). The theories applied as well as their combination enforce interdisciplinarity, i.e. problems to be analyzed from different disciplines and perspectives (Guba & Lincoln, 1994). In the present study, theories include innovation system theory and transaction cost economics; while concepts applied are (policy) learning (sociology, economics), market development (economics), technology development (technical studies), actors and networks (sociology, economics), policy evaluation (policy-oriented research).

In terms of research methods, the empirical research reported here is based on *case study methodology* and *triangulation*; these are typically applied in policy learning and innovation studies. Case study methodology is “an empirical inquiry that investigates a contemporary phenomenon within its real-life context ... [and] relies on multiple sources of evidence” (Yin, 2003). Case

studies often include both qualitative and quantitative approaches to investigate ‘reality’ by triangulating both data (facts and values) and methods (Chen, 1990; Fischer, 1995). Triangulation, as an approach closely related to case study methodology to research multiple sources of evidence, employs various data sources, methodologies and theoretical perspectives to investigate specific phenomena in the field of study (Denzin, 1978). Triangulation is also a means to strengthen the position, the findings and the validity of the research (Kvale, 1997).

3.2 Research methods

The case study is the unit of analysis of this research. Case studies provide insights and foster understanding of contemporary phenomena and thus are often used in research oriented toward policy and technology change. Case studies typically investigate how, when and why certain events occur. By focusing on processes and accommodating descriptive, explanatory and interpretative efforts (Yin, 1994), case studies are a flexible and valuable approach in policy learning and innovation studies (Hakim, 2000). The flexibility of case studies can also be depicted in the different focal issues, i.e. when analyzing processes the entire process is not necessarily under the analytical lens. Instead, certain elements are picked and investigated based on certain criteria. In this research, for example, processes of technology development, market development, actors’ interaction and learning are described. The role of policy is observed in detail and to some extent explained to gain insight and generate knowledge for policy learning. The contribution to knowledge and the context of which case studies reside (countries, cultures and paradigms) are also important. The main limitations of case studies lie in the validity of the research. In terms of internal validity, case studies often have a subjective element. For external validity, general conclusions are often difficult to draw from such context-specific and process-oriented research. To address some limitations of case studies and the interpretative tradition, multiple methods and multiple cases are typically applied for data collection and data analysis (Marsh & Furlong, 2002).

The methods of reasoning in this research include a mix of deductive, inductive and abductive approaches³⁷. The deductive approach (applied in policy

³⁷ Based on Bryman (2004), deduction is the process of deriving consequences of a hypothesis; induction builds up a hypothesis based on observations and patterns, and abduction is an “inference to the best explanation” through successive approximation (Sober, 2008).

learning), the innovation system approach and transaction cost economics provided a frame to the research, where certain factors of the framework could be tested and confirmed (Bryman, 2004; Flick, 2006). The inductive approach was applied when analyzing the concept of learning, the development of components in the innovation system and evaluating energy efficiency policies. Through this approach, patterns could be identified and explanations of technology innovation could be provided. The abductive approach was also used in this research, in particular, in the analysis of learning conditions, learning processes and the role of policy instruments for energy efficiency in buildings. This approach was used because it is believed that both the observed reality and the conclusions are important, but it is also acknowledged that the premises³⁸ might not guarantee the conclusion.

3.2.1 Data collection

The main methods of data collection applied in this thesis are literature review and interviews. Depending on the specific objective of the different papers, the depth of the case and feasibility, these methods are applied to varying extents. In addition, due to the contemporary nature of the problem conferences, topical workshops and formal and informal discussions with experts in the field are also used to gain a more up-to-date understanding of the topic.

The *literature reviewed* and the texts studied mainly include academic literature and documentary materials. Academic literature originates from scientific databases and consists of peer-reviewed and specialized journals, books and conference papers. Documentary materials include officially published documents, such as project reports, workshop materials, seminar presentations, institutional publications, market statistics, legal texts and policy documents. The academic and documentary literature was reviewed for both facts and insights about the cases in relation to the paper-specific research objectives.

Interviews are the most typical sources of case studies and are also used in this research (Tellis, 1997). Interviewees were selected based on professional

³⁸ In this context, premise is understood as a statement of an argumentation which justifies a conclusion.

occupation and expertise in the field of study; the snow-balling technique was often used to identify interviewees. Due to the focus of the research, interviewees were mainly selected from the private sector, representing technology and building manufacturing industries, but actors from the public sector and academia were also interviewed (see Appendix A). In the five papers, close to 100 interviews were conducted. The interviews were carried out in two rounds when feasible; the first round was informative (fact-oriented) and the second round discursive (value and perception-oriented). Discursive interviews were needed to investigate the problems surrounding energy efficiency and policy issues; these types of interviews are more common when the topic is less studied and when the data availability is limited or beliefs and perspectives are researched (K. Hastings & Perry, 2000). The interviews were semi-structured and based on interview protocols (see Appendix B), which on request were sent out to the interviewees before the interview. In some cases, the interview protocol was treated as a questionnaire by the interviewee and was answered in a written form. Unless requested otherwise, the interviews were recorded and transcribed by the researcher and the transcription was confirmed by the interviewees. Depending on the feasibility, the interviews were conducted in person or on the phone with a typical duration between half an hour and three hours. Informal discussions at topical workshops and seminars were conducted in a conversational manner in the form of open-ended questions; notes were taken during or after the discussions³⁹. The topics of the interviews and conversations were shaped by the specific objective of the different papers.

3.2.2 Data analysis

The main methods of data analysis are policy analysis, discourse and text analysis, learning process analysis and transaction cost analysis. These analyses are embedded in an innovation system approach.

Policy analysis, in this research, is applied as an analytical tool of policy evaluation to gain more knowledge on the performance of policy instruments. Policy analysis is viewed as part of the public policy development process, which can be described by the following steps: (i) problem definition based on evidence, (ii) alternative policy formulation based on criteria, (iii) *ex-ante* evaluation of policies and criteria, (iv) policy

³⁹ The events the researcher attended for the purpose of this study are listed in Appendix C.

implementation and (v) *ex-post* evaluation (Bardach, 2000). In this research, policy analysis is applied as an *ex-post* evaluation with the aim of depicting the role of policy instruments as a partial cause of changes and processes leading to these changes in the innovation system. Changes and process here are called policy outcomes and described in terms of developments, such as technology development, market development (diffusion), actors and networks, learning, and cost development (including transaction costs). Policy analysis, embedded in the innovation system approach, is applied in policy-oriented studies to assess, in this context *ex-post*, causal relationships between policy instruments and their outcomes.

Discourse and text analysis studies the rhetoric manifested in the interviews and the content of texts examined in academic and documentary literature (Edwards & Potter, 1992). Discourse analysis involves a consistent and systemic data analysis seeking for patterns in processes, actions and concepts related to technology development, market development, actors and networks and energy efficiency policy with a focus on buildings. The patterns were coded and compared to find, for instance, similarities, differences and deviations from the patterns. Aligned with the system approach, the discourse analysis studied patterns of the development of system components, patterns of relations and patterns of interactions among system components, actors and factors (Churchman, 1979).

Learning process analysis studies the conditions and context of learning in relation to emerging energy technologies (Kamp, et al., 2004). The analysis involves the identification of the most relevant factors facilitating different learning processes (i.e. learning conditions) and the assessment of the context in which learning takes place. The subject of analysis includes such questions as who is learning, what is learnt, how it is learnt and why it is learnt. Learning process analysis, embedded in the innovation system approach, is applied in innovation and policy-oriented studies to assess causal relationships between system components. Specifically, in this research it is applied to whether and how learning processes facilitate technology development and diffusion, interaction among actors and formation of networks, and whether and how different policy instruments support different learning conditions and thus different learning processes. Learning process analysis can be seen here as a tool of the innovation system approach, conceptualizing and establishing causal relationships among complex issues (Haraldsson, 2004; Olsson & Sjöstedt, 2004).

Transaction cost analysis is a principal tool of new institutional economics. It studies the decisions, actions and interactions of actors manifested in transactions and expressed as the cost of transaction (Ménard, 2004b). The analysis focuses on the identification of the nature (source) and the scale (magnitude) of transactions. To support the analysis, sources of transaction costs were reviewed in the energy policy literature, their occurrence was tested through literature review and interviews in the case study and classified based on the categories established by Mundaca, et al. (2013): a) due diligence (search for and assessment of information), b) negotiation, c) approval and certification, d) monitoring and verification and e) trading. The research also obtained data to estimate the scale of transaction costs borne by two relevant actors, the building owner and the building developer, and placed it in relation to the total investment cost. In line with the system approach, transaction costs are considered over the lifecycle of an energy efficient retrofit project and the causal relations among system components are assessed based on the exchange of money, i.e. transactions.

3.3 Reliability and validity

The reliability and validity of the results is important for the credibility and the interpretation of the research outcomes (Yin, 1994). The peer-review process of scientific journals in which the appended papers are published or under review is the cornerstone of the reliability and validity of the research presented in this thesis.

To ensure the *reliability* of the research, triangulation played an important role to cross-check information and insights by applying different data sources (including different informants), methodologies and theoretical perspectives. For example, when the text analysis and the insights derived from literature review left questions unanswered, the analysis was complemented with tailor-made interviews for the specific purpose of double-checking the preliminary findings in question. The documentation of case studies, data availability, data sources and methods throughout the research process increase the reliability of the research. In addition, the use of methods and the findings were reinforced by the peer-review process of scientific journals and books in which the appended papers were published.

To ensure the *internal and external validity* of the research, several approaches were taken. The internal validity, i.e. sound findings in relation to the research objectives, was strengthened by a multiple-sourced literature review, presentations at international conferences, discussions at topical

seminars, courses, summer schools and site visits (e.g. testing institute, national and regional fairs, construction sites). In addition, the anonymous peer-review process of journals and conferences and triangulation of data sources (e.g. market statistics with interviews) and methods (e.g. literature review and interviews) greatly strengthen the position and internal validity of the research (Kvale, 1997). In terms of external validity, due to the context specificity of case studies, generalization of the research topic is approached with caution. Still, the findings and insights are valuable input to policy learning in the field of energy efficiency policy.

CHAPTER FOUR

“The consequences of things are not always proportionate to the apparent magnitude of those events that have produced them.”
Charles Caleb Colton

4. Key Findings and Case Analysis

The research presented in this thesis seeks insights into the role of policy instruments in supporting energy efficient buildings in order to feed into the knowledge base of policy learning. Most energy can be saved through optimizing the heating demand in buildings, for instance by improved insulation or heating measures. Applying these measures, the heating demand can be reduced by up to a factor of eight (e.g. Ürge-Vorsatz, Harvey, et al., 2007). For this purpose, the five papers (case studies) were chosen to focus on building envelope technologies such as energy efficient windows (Papers I and III) and mineral wool insulation (Paper II), heating technologies such as ground-source heat pumps (Paper IV), and energy efficient building systems such as the passive house concept (Paper V). Addressing the first research aim (see Section 1.3), different energy efficient technologies were assessed using different conceptual frameworks of innovation systems, learning and transaction costs and different geographical scopes. Addressing the second research aim, the effects (in terms of outcomes) of policy instruments were assessed, specifically in relation to the introduction and diffusion of energy efficient windows, mineral wool insulation, and ground-source heat pumps (Papers I-IV). Addressing the third research aim, key factors were identified influencing the performance of policy packages for more energy efficiency in buildings. In Paper V, barriers to energy efficiency were explored and transaction costs of the implementation of passive houses were assessed. This was done with the aim of providing insights for future policy design to overcome these barriers. See Table 4-1 for the characteristics of the five appended papers presented in this Chapter.

Table 4-1. Characteristics of the appended papers

	Technology	Country	Conceptual Framework	Policy Outcome
Paper I	Window	Sweden	Innovation system theory, Learning	Technology development, Market development, Cost development, Learning
Paper II	Insulation	Sweden Germany United Kingdom	Sectoral innovation system theory, Learning	Technology development, Actors and networks, Learning
Paper III	Window	Sweden Germany United Kingdom	(Innovation system approach)	Technology development, Market development
Paper IV	Heat pump	Sweden Switzerland	(Innovation system approach)	Technology development, Market development, Cost development
Paper V	Passive house	Sweden	Transaction cost economics	Actors and networks

4.1 Paper I – Energy efficient windows (Sweden)

4.1.1 Objective and approach

The objective of this paper was to provide insights into *how different policy instruments have supported the development and diffusion of an energy efficient technology*, windows, in one country, Sweden. In addition, the study aimed to assess *how different policy instruments can facilitate learning processes* in the innovation system.

The approach this study applied to assess the effects of policy instruments had three starting points. The first lies in the *innovation system theory*; namely that learning is one of the key drivers of technology innovations, i.e. introduction and diffusion of new technologies. Thus, if there is learning in

the system, the likelihood of technology and market development is high. The second is related to learning and *learning process analysis*. It is assumed that learning is present in the innovation system, if the relevant *conditions for learning* are present. For that purpose, based on Kamp, et al. (2004), the conditions for different learning processes (i.e. learning-by-searching, learning-by-doing, learning-by-using and learning-by-interacting) were outlined and their presence or absence were investigated. The third starting point is related to policy evaluation and policy analysis. Whether the outlined learning conditions were supported by policy instruments was assessed. Based on the above, it could be assumed that under the conditions that learning conditions were present and supported by policy instruments, policy instruments affected learning processes and in turn on the introduction and diffusion of energy efficient windows. In other words, policy instruments affected the technology development and market development, including cost development and actors' interactions and network formation related to energy efficient windows.

This case served as a reference point and guide for the papers to follow, in terms of the conceptual framework, research methodology, policy outcome assessment and the actual trajectories of technology development and market development.

4.1.2 Results

This study shows that, based on the learning process approach, different policy instruments have contributed to the technological improvement and market diffusion of energy efficient windows in Sweden. This study also shows that various policy initiatives played an essential role in supporting different learning processes; and that a mix of different learning processes was needed for the development and diffusion of technologies.

The thermal performance of best available Swedish windows improved from 1.8W/m²K in the 1970s to 0.7 W/m²K in 2010; in the same period, the market share of energy efficient windows increased from 20% in 1970 (average U-value of 2.0 W/m²K) to 80–85% in 2010 (average U-value of 1.3–1.2 W/m²K). These developments in technology, markets, costs, and the interaction among actors and formation of networks were supported by policy instruments.

The early *technology development* of energy efficient windows in Sweden was supported by building codes, technology procurement and testing activities.

Both the building codes of the 1970s and the technology procurement in the mid 1990s had stringent energy performance requirements for windows. Technology development in the 2000s was facilitated by energy labelling and the voluntary passive house standard.

Market diffusion of energy efficient windows in Sweden was facilitated by the early and stringent building codes of the 1970s and subsidies coupled with energy performance requirements of the 2000s. However, the short-term nature of the subsidies might have jeopardized long-term industry investments and thus the cost reduction potential of energy efficient windows.

The *interaction among different actors* and the development of networks was facilitated by the technology procurement programme, which included testing, the Energy Performance of Buildings Directive (EPBD) directive, energy labelling and the passive house standard. Important contacts emerged in the frame of the procurement programme between the testing institute, window manufacturers and building companies. New policies and approaches, such as the EPBD and passive house standard in the 2000s, grounded the mutual interest and a common language between involved actors, i.e. window manufacturers, building companies and authorities.

In terms of learning, the study shows that *policy instruments have facilitated individual learning processes in the innovation system* of energy efficient windows. Learning-by-searching was facilitated by public and private R&D, building codes and standards, performance requirements set in financial incentives, and voluntary approaches, such as energy labelling and the passive house concept. Learning-by-doing and learning-by-using were facilitated by technology procurement, and various financial incentives, such as subsidies, tax exemptions and short-term loans. Learning-by-interaction was more prominent in the 2000s and was facilitated by the EPBD, energy-labelling of windows and voluntary buildings standards. Technology procurement supported all four learning processes: learning-by-searching was supported by buyers' requirements; learning-by-doing was supported by testing; learning-by-using was supported through active buyers; and learning-by-interaction was supported by the inclusive and interactive nature of the programme.

4.2 Paper II – Improved insulation (Europe)

4.2.1 Objective and approach

The objective of this paper was to analyze the *introduction, development and diffusion of one energy efficient measure, mineral wool building insulation*, in three selected countries, Germany, Sweden and the UK and to investigate the role of policy instruments in supporting processes of technology development, actors' interaction, networks formation and learning.

The *sectoral innovation system approach* was applied to assess the role of policy instruments, with the starting point that policy instruments, as an essential component of the innovation system, influence other system components and vice versa. Other system components of the sectoral innovation system included *technologies* (products), *actors* (agents), *networks* (interactions), and *learning* (Malerba, 2002). The system components were described by factors facilitating change in the system. Technology development, for instance, was facilitated by the direction of search and development, research & development (R&D), the management of new knowledge, and testing (for more details on facilitating factors, see Paper II). These factors, based on the approach used in Paper I, were also found to be relevant *conditions for learning*. Policy instruments present in the innovation system were identified through literature review. The interaction and influence of system components, including the influence of policy instruments on other system components, were assessed through innovation and policy specific literature review triangulated with expert interviews. As the different factors describing system components were also relevant learning conditions, the literature review and interviews on the presence of policy instruments provided good indications of the influence of policy instruments on various learning processes. Based on the above, it could be assumed that when certain policy instruments were present, those instruments had a high probability of influencing technology development, the interaction of market actors, the formation of networks and certain learning processes related to the introduction and diffusion of mineral wool insulation.

This case built on Paper I in terms of the conceptual framework of learning processes, the knowledge base of learning, and research methodology. Here, the geographical scope was extended to three countries and, to explore the application of innovation systems for policy assessment, one out of the innovation theories encountered in Paper I, sectoral innovation system theory, was applied.

4.2.2 Results

The study shows the role and the effect of different policy instruments in the sectoral innovation system. More specifically, it shows that different policy instruments have, to varying extents, contributed to the development of certain system components, such as technology, market actors and networks, of the sectoral innovation system of mineral wool building insulation in Germany, in Sweden and in the UK. This study also provides insights into policy instruments that supported key learning processes.

The thermal performance of mineral wool products has improved by about 30% since the 1970s. In parallel, the insulation thickness has gradually increased. This, in turn, has led to increasingly higher market sales volumes over time. Similarly, the interaction of market actors and the formation of networks also intensified over time. Good examples of actors' interactions are the increased use of user-producer feedback-channels, more training and education, and the growing proximity among actors; it is mostly based on mutual interest. The European Insulation Manufacturers Association (EURIMA) and the strengthened national industry associations are examples for the formation of European policy networks. These development processes were to some extent facilitated by different policy instruments.

Private, and to some extent public, R&D, accompanied by testing, have established the base for *technology development* of mineral wool building insulation materials. Early stringent energy performance requirements in Sweden and Germany, and later similar experience in the UK, show that building codes have been influential tools in promoting technology development of improved building insulation. In the 2000s, voluntary low-energy building standards, such as the passive house concept, have come to be key drivers of the development of mineral wool building insulation by pushing high performance products onto the market.

Since the beginning of the 2000s, the *interaction among different actors* and the development of networks was facilitated by the EPBD-induced building codes and voluntary approaches. These policy initiatives forced market actors to focus on system solutions, which, in turn, required more intense collaboration. Enhanced collaboration is particularly important in the insulation industry, where feedback processes are limited. Financial incentives, as experience shows in Germany and the UK, and intense information activities have also been key components of improving the

interaction among actors involved in the innovation system of building insulations.

In terms of learning, the study shows that *policy instruments have facilitated key learning processes in the sectoral innovation system* of mineral wool building insulation. Progressive building codes have facilitated learning-by-searching, learning-by-using and learning-by-interacting. Voluntary standards have directly influenced learning-by-searching and learning-by-interacting, and indirectly influenced learning-by-using. Financial incentives have directly supported learning-by-using and indirectly facilitated learning-by-doing. In addition, financial incentives of the 2000s provided a good base for knowledge development in building renovations. The EPBD has given rise to a close collaboration among actors involved with the insulation industry, and thus has greatly supported learning-by-interacting.

4.3 Paper III – Energy efficient windows (Europe)

4.3.1 Objective and approach

The objective of this paper was to analyze the *development and diffusion of one technology, energy efficient windows, in three countries*, Germany, Sweden and the UK, along with the policy instruments applied to support these processes. The study provides a comparison of energy efficient window technology and market development under different policy frameworks in the three countries.

The role of policy instruments was investigated by crossing the *assessment of technology development, market development and policy review*. The starting point of the study relies on the innovation system approach, whereby components of the system have an influence on each others' performance. Policy instruments, as system components, can in this way influence other system components and vice versa. The presence of policy instruments in the system and the structure of the market supply were identified through literature review. The interaction and influence of system components, including policy instruments and market structures, was assessed through policy specific literature review triangulated by interviews with key actors. The market structure supply study included parameters like market concentration (e.g. number and size of companies, market share), technology capability (e.g. R&D and experience), product differentiation,

and actors' relations (e.g. networking)⁴⁰. Based on the above, it was assumed that when certain policy instruments were present under certain market structures, those instruments had a high probability of influencing technology development and market development related to the introduction and diffusion of energy efficient windows in the respective countries.

This case built upon the results of Paper I, by extending their scope and comparing them to other countries, methodologies, and policy outcome assessments of the trajectories of technology development and market development. The study also built upon Paper II in terms of the geographical scope and the knowledge base of the policy landscape.

4.3.2 Results

This study shows that different policy instruments have supported technology improvements and market diffusion of energy efficient windows in Germany, Sweden and the UK. It also provides indications that different policy instruments and different market structures played important roles in the development and the diffusion of energy efficient windows.

The results show that since the 1970s, windows' thermal performance improved from 3.7 and 3.3 W/m²K to 1.4 W/m²K in Germany and the UK, respectively, and from 2.0 W/m²K to 1.2 W/m²K in Sweden. At the same time, the market share of energy efficient windows has increased. In 2010, Sweden showed the highest share with 80%, then Germany at 45% and the UK was lowest at 15%. Policy instruments facilitated this development to some extent.

Technology development of energy efficient windows was guided by building codes, technology procurement programmes and passive house standards by setting stringent and component-based requirements. Testing activities, being an important component of these policy instruments, have greatly contributed to the development and introduction of energy efficient windows.

⁴⁰ Parameters, such as production capacity (e.g. access to capital), suppliers, competition (e.g. exit and entry barriers), free information flow, and spill-over are also present in the study to a limited extent.

The stringency and timeliness of building codes have been crucial to the *diffusion of high performing windows*. Besides progressive building codes, financial incentives (with minimum requirements), technology procurement and voluntary measures, such as the passive house standard and window labelling have been relevant policy instruments to support market development. In the absence of stringent regulations, for instance, poor window technologies can lock in the market for the following 20-30 years (the expected life-time of windows). In addition, stringent energy performance requirements, which are extended to renovations, can tap the further energy saving potentials of the existing building stock.

4.4 Paper IV – Ground-source heat pumps (Sweden & Switzerland)

4.4.1 Objective and approach

The objective of this case study was *to assess the development of ground-source heat pump systems and their emerging markets in two selected countries, Sweden and Switzerland in the context of the policy development*⁴¹ supporting these processes. It provides insights for future innovation and diffusion policies.

The approach considered *technology development, market development and policy development* as relevant criteria to assess the development of ground-source heat pump systems and their emerging markets. Technology development was characterized by the performance improvement of the heat pump and related technologies and services; market development was characterized by market sales, heat pump costs and actors and networks; policy development was characterized by a historical and chronological review of policy packages and a critical review of their evaluations in relation to technology, market and cost development, as well as in relation to market actors in different countries over time. The assessment, based on critical text analysis, interviews and triangulation, established causal relations between policy packages and the introduction and diffusion of ground-source heat pumps.

⁴¹ In this context, the term policy development is not used in the traditional meaning of policy-making process, involving a straightforward path from problem definition, through implementation to evaluation (Anderson, 1979; Dye, 1981; Jones, 1977; Lindblom, 1980; Portney, 1986; Starling, 1988). Policy development here refers to the historical and chronological evolution of policy instruments applied for the introduction and diffusion of ground-source heat pumps in the past forty years.

This case built upon Papers I-III, in terms of methodology and policy outcome assessment on the trajectories of technology development, market development, and policy development. It also used the knowledge base developed in Papers I-III on the role of policy instruments in relation to other energy efficient end-use building technologies.

4.4.2 Results

The study shows that both in Sweden and Switzerland numerous policy instruments have paved the way for technology development and market diffusion of ground-source heat pumps. This study also provides insights into the characteristics of policy packages applied to support development and diffusion processes, actors' interactions, learning, and in turn cost reductions.

The performance of ground-source heat pumps (COP) increased from 13 to 22% in Sweden (1995-2005) and from 20 to 36% in Switzerland (1992-2002). Since 1993, the market diffusion has accelerated, and the annual sales of ground-source heat pumps have increased by 30% in Sweden and by almost 20% in Switzerland. Between 1985 and 2008, the cost of ground-source heat pumps decreased by 50% in Sweden, and by more than 90% in Switzerland. These developments were facilitated by policy instruments, as described below.

The *technology development* of ground-source heat pumps was supported by continuous public and private R&D, first only for the heat pump devices, later also for the infrastructure, i.e. borehole and drilling processes. Furthermore, technology improvement was supported by the development of test facilities and intensified test activities in the 1970s-80s which later led to quality labelling of heat pump devices and later of entire installations.

Market diffusion was supported through coordinated and strategic policy programmes from the 1990s in both countries. In Sweden, a market transformation programme was launched, aligned with technology procurement, testing, subsidies and information campaigns. In Switzerland, regulations, voluntary standards, subsidies, education activities and intense networking facilitated market development.

The *involvement of different actors* in networks and organizations was facilitated by integrated R&D programmes, technology procurement, and education activities. International research programmes, such as the one funded by the

International Energy Agency (IEA), might also have an effect on the emergence of networks and advocacy coalitions. Research and technology procurement programmes have shaped and further facilitated the interaction between the heat pump industry and a new set of stakeholders, including publicly and privately funded researchers, authorities, and institutions. In both countries, the establishment of organisations for coordinated actions and networking greatly supported the development of ground-source heat pumps.

Technology diffusion, learning and policy programmes for ground-source heat pumps have provided opportunities for cost reductions over time. Policies, such as testing, networking and subsidies, have directly or indirectly contributed to cost reductions. In terms of subsidies in Sweden, however, it was observed that their fragmented and uncertain nature might not have allowed for major cost reductions.

4.5 Paper V – Passive house renovation (Sweden)

This paper originated partly from the technical nature and partly from the policy character of the passive house concept. Passive house is an energy efficient system technology including two of the building envelope technologies, energy efficient windows and improved insulation, assessed in Papers I-III. The passive house standard is also a voluntary approach, gaining increasing importance in the energy efficiency policy agenda. The recast of the Energy Performance of Buildings Directive (EPBD) requires that all new buildings should be at least ‘nearly zero-energy buildings’ by December 2018, at the latest. Passive house technologies and the standard itself are essential tools to meet these requirements, and consequently the diffusion of passive houses is favourable for increased energy efficiency in the building sector. There are, however, plentiful barriers to the implementation and diffusion of passive houses; one of them is transaction costs. In order to improve energy efficiency, barriers such as transaction costs must be reduced. In order to reduce transaction costs, however, more knowledge is needed on their sources and scales.

4.5.1 Objective and approach

The objective of this paper was to provide insights into barriers to energy efficiency, in terms of the implementation of ‘passive technologies’ required by future policy instruments. In particular, the focus of this study was to

explore transaction costs, one of the most relevant barriers to energy efficiency, arising through the application of passive house-oriented retrofitting. In addition, the aim of the study was to explore cost reduction potentials, specifically transaction costs, through actors' approaches.

The *transaction cost approach* was applied to the first passive house-oriented renovation project in Sweden (Brogården, Alingsås) to identify the nature and scale of transaction costs. The *presence* and the *scale* of transaction costs, previously identified in the energy policy literature, was analyzed and triangulated through interviews with involved actors. Transaction cost analysis focused on the *source* and the order of magnitude of identified transaction costs, borne by the building owner and the building developer.

Papers I-IV provided a good basis to identify knowledge gaps in transaction costs for passive houses as well as gaining an insight into European policies for energy efficient buildings. This case also built upon Papers I-IV, in terms of the knowledge base of the development, application and integration of energy efficient technologies and the role of different actors in the Swedish building industry.

4.5.2 Results

The results of this study show that transaction costs of different natures were present and not negligible in passive house-oriented renovations; this might have implications for the application and further dissemination of the concept. The results also show cost reduction potentials, through knowledge development and learning, with regards to passive house renovations.

Three main sources of transaction costs were identified in this study: *due diligence, negotiations and monitoring*. Due diligence costs arose through the search for information in relation to the form of collaboration, passive house technologies and monitoring methods, as well as in relation to the procurement, such as preparation and assessment of applications for building developers and subcontractors. Negotiation costs occurred in relation to project formulation and target setting, as well as in relation to the procurement and subcontracting. Transaction costs of monitoring arose in relation to monitoring of energy and cost savings, energy efficient equipment and maintenance of passive house technologies.

In terms of the scale of transaction costs, results indicate that transaction costs of passive house-oriented renovations were higher than those of conventional renovations. The range, however, varied from technology to technology, from project to project and over time. This analysis shows that transaction costs, of individual technologies implemented in passive house renovations, can be 200% higher than transaction costs of conventional technologies.

In case of Brogården, it was found that strategies undertaken by various actors involved in the renovation project resulted in learning and led to cost reductions, most specifically the reduction of transaction costs. These strategies included new forms of interactions, new channels of information, study visits and demonstration projects. Through these strategies, especially through the 'partnering' form of collaboration, extensive learning and large cost reduction potentials can be realized in the future.

CHAPTER FIVE

*“The significant problems we have
cannot be solved at the same level of
thinking with which we created them.”*
Albert Einstein

5. Conclusions and Reflections

The need for more policy learning in the energy efficiency field is argued for in this thesis. This research provides important inputs for policy learning at different levels. First, it applied approaches for policy evaluation novel to the field of energy efficient buildings, with the focus on policy outcome assessment. Second, it assessed the actual development of energy efficient end-use building technologies, their emerging markets and the role of policy packages in this development. Third, it identified key factors influencing the performance of policy packages for more energy efficiency in the building sector. These inputs enhance policy learning, which, in turn, will contribute to overcoming barriers to energy efficiency to support innovation and to facilitate technology change for a more sustainable future.

5.1 Approaches for policy outcome assessment

The first aim of this research was to explore and apply new approaches of policy evaluation for more energy efficient buildings. To address this research aim, policy outcome descriptors, innovation system and transaction cost approaches were applied. Policy evaluations focused on outcome assessment and energy efficient end-use building technologies. *Policy outcomes were assessed in terms of changes (technology and market development) and in terms of processes (learning processes in the innovation system).* The innovation system approach focused specifically on sectoral innovations and learning processes in the innovation system, from an *ex-post* perspective. The transaction cost approach focused on market and organizational transactions with the aim of providing important inputs to future policy design associated with removing constraints arising with the introduction of new technologies and concepts. The approaches applied provided a feasible framework for (i) evaluating some technical, economic and social changes and processes leading to these changes and (ii) providing some useful empirical and contextual insights for policy evaluation practices. In terms of changes, technology development and market development, including actors' interactions and network formations are key aspects to depict policy outcomes. In terms of processes,

learning in innovation systems and transactions are important illustrations of policy outcomes⁴². The common challenges of these approaches lie in their resource intensity and context specificity. Consequently, these approaches provide limited ability for generalization and theorization.

The innovation system approach responded to the articulated need to consider policies (including policy evaluations) in a broader context, as a part of a dynamic ‘techno-socio-economic system’. Policy instruments, as components of these systems, interact with other system components, such as technology, market actors, networks, and market structure. This approach provided room and flexibility for investigating policy- and non-policy-related processes, interactions and influences among different system components; which in turn can be an important input for policy learning. One of the main drawbacks of this approach was the limited means to measure causal effects and completely disentangle policy and non-policy-related effects, e.g. to what extent policy instruments and other system components influenced the development and diffusion of technologies. In addition, the application of innovation system (and other system) approaches requires the consideration of their dynamic nature. In accordance, the described aspects of development are subjects of continuous reconsideration; it is important for better understanding and advanced re-design of policies.

Studying learning processes in the innovation system helped to unfold the relations among learning conditions, learning processes, the performance of policy instruments and policy outcomes. The assessment was based on innovation studies showing that learning is one of the main processes driving innovations and that its presence and intensity depends on certain (pre-defined) conditions. Identifying the presence of different conditions on one hand helped to identify the presence and nature of learning processes; on the other hand it helped to analyse the development of the technology, market, actors’ interactions and network formation. The policy review, including policy processes and evaluations, helped to depict the influence of policy instruments on different learning conditions, thus different learning processes and different development processes – as policy outcomes. Learning processes, however, were assessed among a limited type of actors and focused on a limited nature of issues: By extending the scope of learning in terms of who has learnt what, how and why, more insights might

⁴² In terms of effectiveness, transaction costs are a decisive factor in policy evaluation, however not addressed in this thesis.

be acquired for policy learning. This remark might already suggest one of the main drawbacks of the learning approach, which lies in its resource intensity, both in terms of data collection and analysis.

The transaction cost approach responded to the need for more policy evaluations on outcomes and understanding barriers to energy efficiency. Outcomes were regarded as (i) a change in actors' behaviour (market response) and as (ii) a process manifested in transactions. The change was depicted in the voluntary passive house approach as a market response of actors in the building sector for more energy efficiency, while actors' behaviour was characterized by decisions based on imperfect information and institutionally framed bounded rationality. Transactions, in this context, were also described as a type of interaction in the (innovation) system, based on monetary exchange and contracting, while learning was understood as knowledge exchange. By identifying the source and scale of transaction costs, this approach helped to characterize barriers to energy efficiency, which is an important input into future policy design both in terms of technology supply and market demand. As the application of 'passive strategies' are already required by the Energy Performance of Buildings Directive (EPBD), these insights are timely and essential for policy learning and future policy design. Challenges found with regards to the transaction cost approach are conceptual and methodological, and related to a variety of factors determining transactions costs, such as technology, project, actors, trust among actors, contract type, availability and quality of information, attributability (who bears these costs), availability and quality of data, data collection methods and methods for the quantification of transaction costs. Based on the above, one can argue that uncertainty and context specificity are intrinsic aspects of the transaction cost approach, calling for caution when interpreting results of transaction cost analysis.

5.2 Policy support for the development of energy efficient technologies

The second aim of this research was to investigate the actual development of energy efficient end-use building technologies and their emerging markets – as outcomes of the various policy packages. In order to describe the role of policy instruments in this context, policy outcomes were assessed in terms of changes such as (i) *technology development*, (ii) *market development (i.e. technology cost development, (iii) market actors and networks)*; and in

terms of processes, such as (iv) learning processes in the innovation system. The role of policy packages in terms of outcomes is described below.

The research shows that for the development and diffusion of energy efficient end-use building technologies *policy packages* are needed. These packages include both traditional policy instruments, such as taxes, and technology specific instruments, such as building codes and targeted subsidies. Policy packages most often include a combination of policy instruments belonging at least to two of the four categories of regulative, economic, informative and voluntary instruments. For instance, R&D is necessary for the development of technologies, but not sufficient (as it is highlighted throughout Papers I-IV) to support innovation and technology change. Government interventions need to consider the emerging market of technologies as well as the involved market actors. It has also been shown that policy packages, following the technology and innovation lifecycle from development through introduction to widespread diffusion, change over time. Consequently, policy instruments may also have to change over time, supporting the argument that energy efficiency improvements require sequencing (NRTEE & SDTC, 2009; Wilby & Dessai, 2010) and that technology change calls for a timely and flexible government approach.

(i) Building codes, technology procurement and voluntary standards play an important role in supporting *technology development*. Building codes with stringent component-based requirements were essential drivers for the introduction of energy efficient windows and improved insulation (Papers I and II). In the case of Sweden, for example, the thermal performance of the best available windows improved from 1.8 W/m²K (1970s) to 0.7 W/m²K (2010) in the past forty years. Technology procurement, in the case of energy efficient windows and ground-source heat pumps, played a relevant role both in the introduction and diffusion of (new) energy efficient technologies (Papers I and IV). The performance of ground-source heat pumps (COP), for instance, increased by 13-22% in Sweden (1995-2005) and by 20-36% in Switzerland (1992-2002). Voluntary approaches, such as the passive house standard, have served as a guidepost for the development of high-performance technologies and technology change (Papers I, II, III and V). Testing, as a part of or coupled to building codes, technology procurement and the passive house standard provided essential support to establish a reliable and legitimate technology to introduce to the market.

(ii) *Market development*, in terms of technology diffusion, was typically supported by policy packages, including some type of regulatory

instruments, such as building codes, coupled with economic incentives, most commonly subsidies (Papers I, III and IV). In Sweden, for instance, the market share of energy efficient windows increased from 20% in 1970 (average U-value of 2.0 W/m²K) to 80–85% in 2010 (average U-value of 1.3–1.2 W/m²K). In certain cases, policy packages were extended with voluntary approaches, education of building professionals and extensive information provision (Papers III and IV). For example, in the case of ground-source heat pumps, the market diffusion accelerated since the early 1990s showing an annual sales increase of 30% in Sweden and close to 20% in Switzerland. Cost reductions over time, for instance in the case of heat pumps, were also captured in the form of a learning curve, expressing investment costs as a function of cumulative deployment and highlighting the different market conditions and technological maturity in Switzerland and Sweden (Paper IV). Between 1985 and 2008, the cost of ground-source heat pumps decreased by 50% in Sweden, and by more than 90% in Switzerland. However, subsidies alone were shown to jeopardize the long-term investments in energy efficient technologies and did not support cost reductions (Papers I and IV). Cost reductions were also achieved through voluntary approaches; for instance, at the managerial level private actors used procedure standardization, full life-cycle cost accounting and learning via project bundling (Papers I and V).

(iii) *Market actors and networks*, in terms of the interaction among actors and the formation of networks, have typically been supported by the EPBD and the passive house standard, both requiring system solutions, which in turn calls for more intense interaction, information and education among different professions and actor groups (Papers I-V). In the case of energy efficient windows and ground-source heat pumps, the technology procurement programme created mutual interest and more interaction, for instance, between the testing institutes, window manufacturers and building companies for the development of better performing products (Papers I and IV). In Switzerland, networking was an essential driver of the diffusion of ground-source heat pumps (Paper V). In case of mineral wool insulation, European policies, growing recognition of mutual interest and a strong international industry association strengthened national industry associations and provided a good base for the formation of policy networks (Paper II).

(iv) This research shows that policy packages are needed to support *learning processes*; the characteristics of packages depend on the ‘learning-how’. Four learning processes were assessed throughout Papers I and II; the

results of Paper I show that technology procurement was an essential support for all four learning processes. Building codes and voluntary standards, in combination with R&D and testing, facilitated learning-by-searching. Learning-by-doing requires time and high production rates delivering more products to ‘practice’ on. Policy packages, facilitating these conditions, included technology procurement, testing and economic incentives. Learning-by-using was often found to be neglected in the supply chain of the assessed technologies and also lacked policy support; it calls for actions to develop and support strategies for learning in product use (Papers I, II, and IV). Learning-by-interaction was supported by policy instruments demanding system perspectives and system solutions, such as the EPBD, the EPBD-induced building codes, and voluntary energy efficient house concepts, such as ‘Minergie’ and ‘Passivhaus’. Networking also played an important role for learning and spill-over, both in national and international contexts. In addition, initiatives of private actors, such as building owners or developers of passive houses, were found to promote learning and cost reduction. These initiatives included new forms of collaboration, meeting platforms and information channels, as well as organizational awareness-raising, including study visits and demonstration projects (Paper V).

5.3 Key components of policy packages

The third aim of this research was to identify key components influencing the performance of policy packages promoting energy efficiency in buildings. Based on the research presented in this thesis, these key factors were found to be building codes, networking, testing and voluntary approaches.

Building codes are shown to be an important policy option considering the diversity of technology and market responses across economies. This is in spite of the experience that regulations often serve to phase out laggard technologies from the market. In case of the studied building envelope technologies, building codes were essential components of policy packages, and paved the way for the introduction and diffusion of technologies with improved thermal performance.

Networking and actors’ interactions can be as important as subsidies for the diffusion and cost reductions of energy efficient technologies. When the main direction of technology change is to enhance the diffusion of a familiar technology, actors’ interaction is necessary (e.g. in terms of energy efficient windows and insulation) and when there is a discontinuity in the

system, the role of different networks, such as science-technology networks (e.g. in terms of ground-source heat pumps and passive houses) is exceptionally important. A lack of interaction was expressed, for instance, among actors in the window and insulation industry, which is clearly reflected in the diffusion rates of energy efficient windows in Germany and the UK. The support for building and strengthening actors' interaction and networks is essential to improve strategic integration, to ensure feedback and learning, and consequently to advance energy efficient technology innovation.

Testing and certification are shown to be essential for (new) energy efficient technologies to gain credibility and legitimacy in the market. By requiring testing and certification, policy instruments (such as R&D initiatives, building codes, technology procurement programmes and subsidies) greatly support stable market development. In addition, for the development of energy efficient technologies, entrepreneurial testing, as a stable strategy, was essential for the industry to make long-term investments in standardised products. For instance, by establishing a system for quality assurance, reliable products and high-level public acceptance for ground-source heat pumps were created both in Sweden and Switzerland.

The *voluntary passive house approach* seems to be a strong driver of technology development and actors' interaction. By providing an important guidepost for emerging energy efficient technologies, through its stringent energy performance requirements, the passive house standard drives technology change and facilitates learning-by-searching. Through the search for system solutions, the passive house approach also facilitates actors' interaction and network formation, and consequently learning-by-interacting. During the process of searching for (new) energy efficient technologies and developing (new) energy efficient system solutions, actors acquire more knowledge and learn over time, from one project to another. As the case of the Swedish passive house-oriented renovation shows, knowledge development and learning ultimately result in significant cost reductions at different actors' stake.

All in all, it can be concluded that technology change, and in particular the development of energy efficient end-use building technologies and their emerging markets, requires long-term and flexible policy support. Policy support includes diverse policy packages, rather than individual policy instruments; however some policy instruments, such as building codes,

voluntary approaches, and policy-induced activities (such as networking and testing), are shown to be key components of these packages.

5.4 Contribution of the thesis

The research presented in this thesis is an important input for policy learning for energy efficiency in buildings, innovation and technology change. The assessment of the policy incentives applied in various countries to support the development of energy efficient building technologies and their market emergence illustrate some important characteristics of policy learning, both in terms of methodological and empirical findings.

The *methodological* contribution of this research is to the knowledge base of energy efficiency policy evaluation approaches. First, it applied the innovation system approach, specifically the sectoral innovation system approach, the concept of learning as an analytical tool, and the transaction cost approach to evaluate *ex-post* and *ex-ante* effects of policies. Second, it assessed policy outcomes through market responses to energy efficiency policies, such as technology development, market development, actors and networks, and learning processes.

The *empirical* contribution of this research is to the knowledge base of the characteristics of policy outcomes in relation to energy efficiency policy implementation. The case studies, in terms of their content and/or approach, are novel within the field of energy efficiency policies for buildings. The research includes innovation case studies on three energy efficient building technologies, energy efficient windows, mineral wool insulation, and ground-source heat pumps in four European countries, and a case study on transaction costs in a passive house-oriented retrofitting in Sweden. This knowledge is of high relevance for tackling barriers to and designing policies for more energy efficiency in the building sector.

5.5 Further research

While conducting this research, various theoretical and empirical issues were identified for further research; two of them are highlighted below.

From a theoretical and methodological perspective, the issue of disentangling the effects of different policy instruments from each other and from the effects of other system components calls for new

perspectives, approaches and methods to explore. Closely related to this issue, identifying the actual causal effects between the policy instruments and policy packages and system changes also requires new and resourceful ways to apply policy evaluations.

From an empirical perspective, the need for more policy evaluation is accentuated. Policy evaluation in the energy efficiency field has a relatively short history and knowledge base to learn from. As has been emphasized before, policy evaluations have been more impact-oriented, while policy outcomes related to changes and processes, in particular market and institutional responses and actors' behaviours, have received limited attention. In this context, the need for research on local, regional, sectoral and national learning is emphasized along with the increasing need for potential policy support in this field.

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Appendix A – Interviews

The table presents interviews as data sources of the appended papers. Due to business confidentiality, companies and the names of interviewees are not disclosed.

Publication	Type of organization	Occupation of informants	Number of interviews
Paper I	window manufacturer (13), window retailer (1), glass manufacturer (1), industry association (1), authority (1), testing institute (1), university (1), consultant (2)	managing director (4), product developer (6), marketing and/or sales manager (6), other (7)	30
Paper II	insulation manufacturer (5), industry association (5), authority (1), consultant (1)	managing director (1), product developer (3), marketing manager (3), other (7)	14
Paper III	window manufacturer (12), industry association (6), glass manufacturer (1), university (1), consultant (1)	managing director (3), product developer (5), marketing and/or sales manager (4), other (10)	22
Paper IV	heat pump manufacturer (5), industry association (1), authority (1), testing institute (1), university (2)	marketing and/or sales manager (5), other (5)	11
Paper V	building owner (1), building developer (1), authority (1), architect (3), testing institute (1), university (1), consultants (2), tenants' association (1)	managing director (1), financial manager (1), building project manager (1), development manager (1), others (10)	14

Appendix B – Interview protocols

General interview protocol investigating the development of energy efficient end-use building technologies and their emerging markets (Papers I-IV)

Technology development

1. Describe the historical development of the respective energy efficient technology, with the focus of improvements in terms of thermal performance (windows, insulation) and efficiency (ground-source heat pumps).
2. Which are the most relevant milestones in product and process development from market diffusion and cost reduction point of view?
3. Which are the most relevant technical factors that influenced market and cost development of the respective energy efficient product?
4. What has triggered the development of more energy efficient products?

Market development

1. Describe the market development of the respective energy efficient technology (windows, insulation, ground-source heat pumps), with the focus on production, market sales, market share of energy efficient products, product assortment.
2. Which are the most relevant milestones (changes) in the product assortment in general and from an energy efficiency point of view?
3. How has the introduction of energy efficient products affected the whole market?
4. Describe the relevant manufacturers (and their market shares) present on the market now and when the development of respective energy efficient products started. (Describe the role and magnitude of import and export.)
5. What has influenced the diffusion of energy efficient products? (Optional: demand, cost, energy savings, environmental consciousness, policy...)

Cost development

1. Describe the (internal and external factors) influencing the cost structure of the technology?
2. How has production intensity affected the cost development?
3. What has influenced the cost development of energy efficient products? (Optional: component prices, demand, competition...)

Actors

1. Describe the actors and their roles from the production of the technology to the end-use installation in buildings.
2. Describe the influence of different actors in terms of technology, market and cost development.

Policy

1. Which are the most relevant factors that have influenced (contributed to / hindered) technology development of the respective energy efficient product?
2. Which are the most relevant factors that have influenced (contributed to / hindered) the market development of the respective energy efficient product?
3. Which are the most relevant factors influenced (contributed to / hindered) the cost development of the respective energy efficient product?
4. Describe the influence of different policy instruments on the technology and market development.

Specific interview protocol investigating learning processes related to energy efficient windows and improved insulation (Papers I-II)

Learning-by-searching

1. Research and development (R&D) (Papers I-II)
 - a. Have you had an R&D department during the following time periods: 1970-1980, 1981-1990, 1991-2000 and 2001-2008?
 - b. How much resources (monetary, human) have you allocated for R&D of energy efficient products over the given time periods?
 - c. What was the direction and focus of R&D activities? (Optional: prototype development)
2. Knowledge development through interaction & collaboration (Papers I-II)
 - a. Have you had collaboration with other universities or research institutes in relation to the development of energy efficient products over the given time periods?
 - b. If yes, which were the collaborating partners and what were the main outcomes of the collaboration?
3. Knowledge development through other measures (education and experience) (Paper I)
 - a. Have you taken other measures to promote knowledge development related to energy efficient windows in the given time periods? For example, internal employment trainings and education, recruitment of employees with special knowledge/experience on energy efficient windows.
4. Technology and knowledge development (Paper I)
 - a. To what extent have other sources/factors influenced the development of energy efficient windows in the given time period? (e.g. conferences, scientific and non-scientific articles, study visits)
 - b. Describe the technology development (and knowledge intake) through examples.
5. Knowledge management (Paper II)
 - a. Have you registered any patents? Describe them.

Learning-by-doing

1. Testing (Papers I-II)
 - a. Have you had the possibility to test product performance over the given time period?
 - b. Where and how do you test your products? (Paper I)
 - c. How have testing contributed to the energy efficiency of the products?
 - d. Describe the development through concrete examples.
6. Production (Papers I-II)
 - a. Have you produced energy efficient windows in the given time periods? (Paper I)
 - b. Describe the production / sales volumes (with figures if available) in the given time periods. (Papers I-II)
7. Product and process changes (Papers I-II)
 - a. Which changes (improvements) have been important in terms of energy efficiency (thermal performance) in your products in the given time periods?
 - b. What has triggered these changes (improvements)?
 - c. Which have been important changes (improvements) in the production process related to energy efficiency in the given time periods?
 - d. What has triggered these changes (improvements)?

Learning-by-using

1. Users demand (Paper I)
 - a. Describe your major customers of energy efficient windows. (Optional: private persons, smaller building companies, larger building companies, others)
 - b. Has the interest/demand changed over time?
 - c. How would you explain such changes?
2. Describe the structure of the supply chain for your products. (Paper II)
 - a. Who are your suppliers and customers? What is the structure of distribution networks?
 - b. Has the supply chain substantially changed over the years?
3. Users experience (Papers I-II)
 - a. Have you followed-up on your customers experience in the use of energy efficient products?
 - b. Do you get feedback from your customers? If yes, in what form?
 - c. How has customer feedback resulted in changes in the product design or the production process?
4. Users involvement (Paper I)

- a. Are your customers involved in the development of energy efficient products? If yes, how?

Learning-by-interacting

1. Interaction and collaboration (mutual interest) (Paper I)
 - a. Have you been actively involved and interacting with other actors on issues about energy efficiency?
 - b. Which actors have you been collaborating with? (Optional: other manufacturers, other companies in the building sector, testing institutions, authorities, actors in other countries)
 - c. What type of interactions have you had? (Optional: common project, R&D, dialogues)
 - d. What kind of advantages have interaction/networking resulted in?
2. Interaction and form of collaboration within the supply chain (e.g. suppliers, other insulation manufacturers, distributors, installers, designers, developers, construction companies, etc.) (Paper II)
 - a. What type of interaction do you have with the installers of your products?
 - b. Do you have direct business connection with them? Has it changed over the years?
 - c. Does the installation of your insulation products/solutions require specific expertise? If yes, how do you communicate this to the installers of your products?
 - d. What is the form of collaboration you have with other actors (e.g. suppliers, other insulation manufacturers, distributors, installers, designers, developers, construction companies, etc)? (Optional: initiatives for public awareness-raising, is this a recent development?)
 - e. Have you been involved in joint initiatives on energy efficiency with any of the actors described above? (For instance, standardization (e.g. CEN/TC 350) or work on the definition of environmental criteria of thermal insulation products? Please outline current status and results.)
3. Trainings for building professionals (Paper II)
 - a. When did you first offer training on energy efficiency to building professionals? What changes have you observed? Whom do you target? Have you received training?
4. The role of actors (Paper II)
 - a. What actors do you think have played a significant role in the development and/or diffusion of energy efficient insulation products?

**Follow-up questions on policy, cost and technology development.
(Papers I-II)**

1. Which factors do you see that were essential in the development and diffusion of energy efficient products?
 - a. Prioritize the influencing factors described below: building codes, subsidies, technology procurement, energy labels, energy declaration, information, voluntary standards, industry-cooperation, lobbying activities, oil prices, building cycles, others? (Paper I)
2. Which factors do you see that were the most influential barriers to the development and diffusion of energy efficient products?
 - a. Prioritize them. (Paper I)
3. How have prices of energy efficient products developed over time?
 - a. My pre-study shows that prices of energy efficient windows have been increasing by an average of 5% over the past 15 years. How does this picture fit with your experience and figures? (Paper I)
4. How has the thermal performance (U-value) of energy efficient products developed over time?
 - a. My pre-study shows the following development of U-values of windows. (Paper I)

Specific interview protocol investigating transaction costs of passive house-oriented renovation project in Sweden (Brogården, Alingsås) (Paper V)

Barriers of passive house renovation (vs. BaU renovation)

1. Did you face barriers during the renovation process? If yes, what type of barriers?
2. Did you face barriers of the following types? (Explain.)
 - a. Lack of resources, e.g. knowledge/information/interest of end-users about energy efficiency, developers/contractors, access to capital or financing possibilities
 - b. Uncertainties about energy efficient technologies, e.g. the availability, the performance, the operation, (too high) costs, (too low) price for energy savings
 - c. Difficulties in project coordination, e.g. establishing contacts between actors, implementation (including project replicability), administration / preparation of relevant documents (project design, feasibility studies, administrative procedures, etc.)
 - d. High monitoring (and verification) costs
 - e. Other barriers that you can think of and are not covered above?

Start-up phase (feasibility and conceptual design)

1. Project formulation.
 - a. How much (more) time did it take to decide whether this project will take place?
 - b. Who was involved in this activity?
 - c. How much (more) time did it take to collect and formulate tenants' preferences?
 - d. Who was involved in this activity?
2. Target setting.
 - a. How did the target setting take place? (E.g. activities, meetings, suggestions, stakeholder dialogues, etc.)
 - b. How much (more) time did 'target setting' (the particular activity/ies above) take?
 - c. Who was involved in setting these targets?
3. Preparation. Feasibility study.
 - a. Has there been a feasibility study done on the renovation project? If yes, what was the focus content of the study? (passive principles, tenants' preferences)

- b. How much (more) time did it take to do the study?
 - c. Who was involved in this activity?
 - d. How much time did it take to study the passive house principles?
 - e. Who was involved in this activity?
4. Strategy design and its approval.
- a. How much time did it take to decide and get approved that the entire project is going to be a passive renovation?
 - b. Who was involved in the decision-making and approval process?
5. Information provision to tenants.
- a. Do you (need to) give information to the users, e.g. on energy efficiency? If yes, how much (more) time does it take to prepare and provide this user information?
 - b. Who is responsible for preparing / providing this information?

Planning of the pilot project

1. Planning meetings.
- a. How many planning meetings have there been?
 - b. How much (more) time did they take (because of the passive nature of the renovation)?
 - c. Whose responsibility was it to run these meetings?
 - d. Who were the typical participants of these meetings?
2. Partnering.
- a. How much (more) time did it take to set up partnering / to get the partners on board / to accept the offers for all building projects?
 - b. How much (more) time does it take to manage activities related to partnering?
3. Investigation.
- a. How much (more) time did it take to arrange the investigation of the pilot buildings?
 - b. How much (more) time did the investigation of the pilot buildings take?
 - c. How much (more) time did it take to define and administrate the problems found in the buildings during the investigation? (...and get them aligned with the overall goal of the renovation project?)
 - d. Who was involved in this activity?

Implementation of the pilot project

1. Tendering.
 - a. How did you prepare for tendering? (What kind of activities did it involve?)
 - b. How much (more) time did it take to prepare for and to run tendering? (Due to the decision on partnering it was said that the preparation took long and the rest? organization, running, follow-up, etc.)
 - c. Who were involved in the preparatory activities and the tendering procedure itself?
2. (Sub-)Contracting.
 - a. Do you have (already) contracted partners (suppliers, installers, etc.) whom you were about to work with on the Alingsås renovation project? If not, how much (more) time did it take selecting subcontractors for this project? (searching, acquiring, assessing information)
 - b. Do you have template contracts? If not, how much (more) time did it take to prepare the contract(s) for this project?
 - c. Who was involved in this activity? (e.g. drafting, signing/approving, external consultant/third party/lawyer)
 - d. If external parties were involved, how much (more) did they cost?
3. Building process / implementation.
 - a. How much (more) time did it take to find solutions for the “problems”/”deficiencies”?
 - b. How much (more) time do you spend with project coordination and administration?
4. Building process / implementation coordination.
 - a. Fixing the time, both with the tenants (and the installers) takes time. Who does the time arrangements?
 - b. How much (more) time does it take?
5. Building process / implementation meetings.
 - a. Is it a common practice to have process meetings? If yes, how often are these meetings organized generally and how often were they held in this particular project?
 - b. How much (more) time did these meetings take?
6. Training.
 - a. How much (more) time did it take to arrange / to participate on training (or educational) session(s) related to the passive house concept?
 - b. Who initiated, arranged and ran these activities?

Follow-up of the pilot project

1. General experience.
 - a. How much (more) time did it take to collect experience from actors?
 - b. Which actors did you collect information from?
 - c. How much (more) time did it take to build the database?
 - d. How much (more) time did it take to manage the database?
 - e. Who was involved in these activities (collecting info, building and managing database)?
2. Tenants' preferences.
 - a. How much (more) time did it take to measure tenants' satisfaction? / Follow-up the fulfilment of tenants' preferences?
3. Technical measures. Energy savings and GHG savings.
 - a. How much (more) time does it take to monitor the technical measures, energy and GHG savings?
 - b. Who is involved in monitoring?
 - c. How much (more) time does general maintenance take (in comparison to a regular building after renovation)?
 - d. Who is involved in this activity?
4. Economic administrating and monitoring.
 - a. How much (more) time does it take to administer and monitor project financing?
 - b. Who is responsible for this activity?
5. Certification.
 - a. Have building certification(s) been issued for the energy performance of the building? If yes, how much (more) time does the certification process take?
 - b. Who was involved in this activity?
6. Other – general follow-up question.
 - a. Which of the above “actions” do you see as highly related to the energy efficient nature of the project?

Transaction cost of individual energy efficiency measures in the pilot project

1. Which measures did you make in this renovation that are specific to passive house renovations?
2. Based on your experience, how much (more) time did you spend on this project because of its passive nature?

Slab

1. How much time did it take to decide over the slab insulation? (searching for and assessing information)
2. And the material change of the slab insulation? (discussion on cellular concrete, vacuum insulation)
3. Who was involved in the decision-making process?
4. Did this new material require new expertise? If yes, how much time did it take time to find the resources needed? (How much more time did it take to handle the new technology (cellular concrete) in comparison to the old one?)

Load-bearing frame and inner walls

1. How much time did it take to decide over how the load-bearing structure shall be built? (searching for and assessing information)
2. Who was involved in the decision-making process?

Outer walls

1. How much time did it take to decide over the chosen material: light yellow façade brick? (involving colour discussions)
2. Who was involved in this activity?
3. How much time did the investigation of different façade materials take (plaster, façade brick, and boards)? (searching for and assessing information)
4. Who was involved in this activity?
5. How much time did it take to decide on the removal of the wooden structure?
6. Who/which actors were involved in this decision-making?

Attic

1. How much time did it take to decide how the attic would be made energy efficient? (searching for and assessing information)
2. Who was involved in the decision-making process?
3. How much time did you spend on looking for and assessing information on airtight and well-insulated roof hatches?
4. Who was involved in this activity?
5. How much time did it take to install them?

Windows and doors

1. How much time did it take to choose the type of windows and how they would be installed? (searching for and assessing information)

2. Who was involved in the decision-making process?
3. How much time did it take to carry out evaluations with regards to solar angles before the final design of the windows and balconies were set?
4. How much (more) time did it take to work with cement covered boards (insulation around the windows)?
5. How much time did you spend searching for and assessing information on energy efficient doors?
6. Who was involved in this activity?

Ventilation system (and optimization of space heating)

1. How much time did it take to choose the type of ventilation system? (separate ventilation units in each apartment over a central ventilation system) (searching for and assessing information)
2. Who was involved in the decision-making process? (investigation of different options, cost of negotiation, discussion)
3. How much time did it take to search for and assess information on supply air terminal which were feasible for both heated and unheated air and operated at the flow rates which were needed in the apartments?
4. Who was involved in this activity?

Layout – eliminating thermal bridges at the balconies

1. How much time did it take to involve an additional actor (architect)?
2. Who was involved in the decision-making?
3. How much time did it take to decide to change the design of the balconies? (searching for and assessing information)
4. Who was involved in this activity?
5. How much time did it take to revise and redraw the design?
6. Who was involved in the redesign?

Hot water system

1. How much time did it take to decide how the hot water system would function? (searching for and assessing information)
2. Who was involved in this activity?
3. How much (more) time did relining of pipes take in comparison to drilling in the new slab?
4. How much time did it take to negotiate with the district heating company to install solar panels?
5. How much time does it take to maintain good cooperation with the local heating company?

Appendix C – Conferences and workshops

The table presents conferences and workshops relevant to the thesis work.

Conference / Workshop	Date	Place	Researcher's role
DIME International Conference on Innovation, Sustainability and Policy	11-13 Sep 2008	Bordeaux, France	Speaker (conference paper)
Energitinget 2008	12-13 Mar 2008	Stockholm, Sweden	Participant
Scientific Conference on Energy and IT in connection to Energitinget 2009	11-12 Mar 2009	Stockholm, Sweden	Speaker (conference paper)
Workshop on "Lågenergihus"	26 Jan 2010	Stockholm, Sweden	Participant
IEPEC International Energy Program Evaluation Conference	9-10 Jun 2010	Paris, France	Speaker (conference paper)
ERSCP-EMSU European Round Table for Sustainable Consumption and Production	25-29 Oct 2010	Delft, The Netherlands	Speaker (conference paper)
Roundtable on Information Instruments to Support Thermal Efficiency Upgrades of Buildings	18 Feb 2011	Berlin, Germany	Speaker
Workshop on "Vägväl Miljonprogrammet"	20 May 2011	Malmö, Sweden	Participant
Workshop on "Möjligheter för miljoner"	20 Sep 2011	Jönköping, Sweden	Participant
Conference on the Performance of the European Building Stock (BPIE)	9-10 Nov 2011	Brussels, Belgium	Participant
Seminar on Sustainable Buildings: strategies and policies	2 Mar 2012	Aalborg, Denmark	Speaker
Sustainable Housing – Second Policy Meets Research Workshop	15-16 Mar 2012	Helsinki, Finland	Participant
Strategies for cost-optimal energy efficient building retrofits	29 Mar 2012	Espoo, Finland	Speaker
Workshop on "Finansiera renovering och energieffektivisering..."	5 Sep 2012	Stockholm, Sweden	Participant
Inspire – project workshop	25-29 Sep 2012	Aalborg, Denmark	Participant
Urban Visions and Challenges	14 Nov 2012	Lund, Sweden	Participant

Appended papers

The following papers are appended to the thesis:

- Paper I:** Kiss, B. & Neij, L. (2011). The importance of learning when supporting emergent technologies for energy efficiency – A case study on policy intervention for learning for the development of energy efficient windows in Sweden. *Energy Policy* 39, p 6514–6524.
- Paper II:** Kiss, B., Gonzalez, C. & Neij, L. (2012). The importance of learning in supporting energy efficiency technologies – A Case Study on Policy Intervention for Improved Insulation in Germany, the UK and Sweden. Article in press *Journal of Cleaner Production*. Available online since 24 December 2012.
- Paper III:** Kiss, B. (2012). Experience in policy intervention for energy efficient windows – in Germany, Sweden and the United Kingdom. *Submitted*.
- Paper IV:** Kiss, B., Neij, L. & M. Jakob (2012). Heat Pumps: A Comparative Assessment of Innovation and Diffusion Policies in Sweden and Switzerland. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.
- Paper V:** Kiss, B. (2013). Exploring transaction costs of passive house-oriented renovations. *Submitted*.

Paper I

Kiss, B. & Neij, L. (2011). The importance of learning when supporting emergent technologies for energy efficiency – A case study on policy intervention for learning for the development of energy efficient windows in Sweden. *Energy Policy* 39, p 6514–6524.



The importance of learning when supporting emergent technologies for energy efficiency—A case study on policy intervention for learning for the development of energy efficient windows in Sweden

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ABSTRACT

The role of policy instruments to promote the development and diffusion of energy efficient technologies has been repeatedly accentuated in the context of climate change and sustainable development. To better understand the impact of policy instruments and to provide insights into technology change, assessments of various kinds are needed. This study analyzes the introduction and development of energy efficient windows in Sweden and the policy incentives applied to support this process. The study focuses on the assessment of technology and market development of energy efficient windows in Sweden; and by applying the concept of learning, it assesses how conditions for learning-by-searching, learning-by-doing, learning-by-using and learning-by-interacting have been supported by different policies. The results show successful progress in technology development and an improvement in best available technology of Swedish windows from 1.8 W/m² K in the 1970s to 0.7 W/m² K in 2010; in the same time period the market share of energy efficient windows increased from 20% in 1970 (average *U*-value of 2.0 W/m² K) to 80–85% in 2010 (average *U*-value of 1.3–1.2 W/m² K). The assessment shows that various policy instruments have facilitated all four learning processes resulting in the acknowledged slow but successful development of energy efficient windows.

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1. Introduction

New and innovative energy technologies are required to meet the challenges related to climate change and sustainable development. This need for technological change has been acknowledged and comprehensively reviewed in numerous studies; governmental incentives of various kinds have been developed to support processes of technical change. Nevertheless, the focus has been on the introduction of technologies for energy supply, whereas less attention has been given to technologies for an efficient energy end-use. This is the case, although most scenarios show that the lion's share of future greenhouse gases reductions relies on a more efficient energy end-use (IPCC, 2007; McKinsey, 2009; IEA, 2010). Accordingly, more attention related to the development and diffusion of energy efficient technologies is required.

To support, or even accelerate, the transition of energy efficiency, governmental policy interventions are required to encourage and complement the private sector's investment in energy efficient technologies. Governmental policy interventions

are needed to reduce market barriers and speed the passage of new technologies from invention to marketplace. To make governmental policy programs effective the design and impact of such programs need to be assessed; this is to provide insights into how various policy strategies have, or have not, supported successful trajectories of new energy technologies. By providing such insights, policy interventions could be improved and essential elements in governmental policy strategies could be identified.

In recent years, a number of studies have assessed the processes of policy intervention for the development and diffusion of various energy supply technologies. Some of the most comprehensive studies have applied a system-oriented innovation approach (see e.g. Bergek, 2002; Neij and Åstrand, 2006); and some studies have even assessed how certain learning processes have affected technology change and how these learning processes can be facilitated by various policy instruments (see e.g. Kamp et al., 2004). Learning is considered a key component and driver in the process of technology change. In all, the evaluations have provided important knowledge in policy intervention of energy supply technologies. To proceed even further, assessments with the focus on policy interventions for the development and introduction of energy-efficient end-use technologies are required.

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The objective of this study is to advance knowledge related to technology change and processes of policy intervention of emergent energy-efficient end-use technologies by analysing the development and diffusion of energy-efficient windows in Sweden and policy instruments applied to support the introduction and development of these windows. The focus is on how various learning processes – learning-by-searching, learning-by-doing, learning-by-using and learning-by-interacting – have been facilitated by different policy programmes. In Sweden, as in most other countries, the building sector accounts for almost 40% of the total energy demand (Energimyndigheten, 2011). Windows alone represent a significant share of heat leakage of the building envelope, therefore they are an important component for meeting today's challenges in using energy more efficiently in the building sector. The study is limited to the policy intervention and the market development of energy efficient windows in Sweden. This scope has been chosen despite the fact that the development of windows has only partly relied on Swedish window manufacturers, also partly on international glass manufacturers (of which three dominates today's market). Although the history of windows in Sweden is long, the focus of this analysis is on energy efficient windows in the past 40 years.

The outline of the paper is as follows: Section 2 provides the conceptual framework of the paper and presents the definition of energy efficient windows, also including a more detailed introduction of the concept of learning, selected learning processes and the conditions for these different learning processes; Section 3 presents the policy setting in Sweden (1970–2010); Section 4 presents the results in terms of technology and the market development and the policy incentives applied to support these processes of change; and Section 5 provides an insight in how different policy instruments have facilitated the essential learning processes supporting technology and market development. In the concluding remarks general policy implications to support technology change and learning are included.

2. Conceptual framework

Over the years, various methods and approaches to analyse technology change have been developed, amongst others the theory of large technical systems (e.g. Hughes, 1983, 1988), the theory of social construction of technical systems (e.g. Bijker et al., 1987), the theory of actor-networks (e.g. Callon, 1987), the theory on innovation systems (e.g. Freeman, 1988; Lundvall, 1988; Nelson and Winter, 1977; Nelson and Rosenberg, 1993; Carlsson and Stankiewicz, 1995; Carlsson and Jacobsson, 1997; Carlsson et al., 2002; Edquist, 1997), the theory of Technology Innovation Systems (TIS) (e.g. Hekkert et al., 2007; Bergek et al., 2008), the theory of national innovation systems (e.g. Lundvall, 1992), theories of learning (e.g. Arrow, 1962; Rosenberg, 1982), theories of technology transfer (e.g. Hirschman, 1967; IPCC, 2000) and additional theories of technology change covering parameters such as spill-over effects, economies of scale and scope, as well as standards and regulation (see e.g. Grübler, 1998). These theories to various extents have also been used to assess the effect of policy programmes on technology change.

In this study, we illustrate how various policy instruments in general terms have effected the development of energy efficiency in terms of technology development and market development (see Section 4). In order to provide better understanding for technology development of windows, the definition of energy efficient windows used in the paper is presented in Box 1.

Moreover, the study illustrates how different policy programmes have facilitated various underlying learning processes effecting technology change. In the innovation literature, learning

Box 1–Energy efficient windows.

The definition of an energy efficient window is a rather vague concept and has changed over time as the performance of the windows has improved. Technically, energy efficiency of windows is measured based on the quality of their thermal insulation, i.e. how much heat is lost through the window surface when the indoor temperature is higher than the outdoor. The thermal performance is expressed with U -value, i.e. the heat flux (Watt) through the window per m^2 at a temperature difference between inside and outside of 1 K or $^{\circ}C$. The lower the U -value, the lower the thermal transmittance of the window, and the better the insulation, thus the more energy efficient is the window. In this paper, we have defined the criteria of an energy efficient window in Sweden over time following the improvement of windows; this based on interviews with different actors involved in the window market, see below.

U-value development of energy efficient windows in Sweden (1970–2010).

Period	Energy efficient window (U -value) ($W/m^2 K$)
1970–1988	≤ 2.0
1989–1997	≤ 1.5
1998–2005	≤ 1.3
2006–	≤ 1.2

is acknowledged by several authors to be a significant driver for innovation, (see e.g. Arrow, 1962; Rosenberg, 1982; Kamp et al., 2004; Lundvall, 2007; Jensen et al., 2007), and several types of learning processes have been identified promoting change in the socio-technical innovation system. In this research, four types of learning processes have been considered: learning-by-searching, learning-by-doing, learning-by-using and learning-by-interacting (see text below).

As learning per se is difficult to identify and measure, this study applies a pragmatic approach focusing on how different policy instruments support essential conditions for learning; for a similar assessment approach see Kamp et al. (2004). Based on a literature review on learning, a framework for policy assessment was developed; this framework covers the most relevant factors facilitating different learning processes for the development of energy-efficient windows (see Table 1). By applying these conditions, we analyse the support for different learning processes and illustrate how they have been addressed by various policy instruments over time. The most relevant conditions for learning and their presence or absence were investigated through interviews with product developers and other representatives of window manufacturing companies, research institutes and authorities as well as other professionals in the field. In total 30 interviews were conducted. The analysis indicates the role of different policy instruments and the experience in success and failure in supporting the innovation path of energy efficient windows in Sweden.

Learning-by-searching is a systematic way of acquiring new knowledge through R&D or learning-by-studying (Garud, 1997). It mostly involves universities, research organisations and/or R&D departments of companies. Results of learning-by-searching mainly appear in different publications, reports and articles, and on the company level, outputs are embodied in prototypes. Kamp et al. (2004) has defined a number of conditions that facilitate learning-by-searching in the innovation literature; Table 1 includes those which we have found relevant in the context of the development of energy efficient windows.

Table 1
Conceptual framework—learning conditions and learning processes.

Learning process	Conditions for learning (A)	Presence of learning conditions (B)	Description of learning conditions (C)
Learning-by-searching	Direction of search and development	Yes/no	Subject of search and development, e.g.: technological guidepost, technological paradigm, applicable scientific theory, standards and/or regulations
	R&D department and resources: time/labour devoted to R&D/capital	Yes/no	Subject of research at R&D, hours/R&D employees/SEK
	Education: knowledge development and experience used	Yes/no	Subject of education, actors involved
	Management of ownership of novelties and new knowledge	Yes/no	Number of registered patents, type of registered patents
Learning-by-doing	Production/production rate	Yes/no	Number of products produced over time
	Testing	Yes/no	Subject of tests (e.g. efficiency, quality), frequency, outcome of tests
Learning-by-using	Education: improving production skills and applying experience	Yes/no	Subject of education, actors involved
	Existence and active presence of users (e.g. demand for energy efficient windows)	Yes/no	Kind of user groups, type of demand
Learning-by-interacting	Contacts between producers and customers-users' involvement in product development	Yes/no	Means of contacts, feedback mechanism, frequency, means and level of involvement
	Actors involved networks and collaboration/interaction	Yes/no	Actors, form of collaboration and network, topics/subjects
	Mutual interest	Yes/no	Drivers of interest, closeness among actors, norms (openness and disclosure)
	Change agents: intermediaries and network builder	Yes/no	Role of change agents

The framework presented in Table 1 is applied in this paper to analyse how different policy instruments support essential conditions for learning for the development of energy-efficient windows. The framework covers the most relevant conditions facilitating different learning processes (column A), their support or non-support of these conditions (column B) and, if possible, a more detailed description of the learning conditions (column C).

Learning-by-doing has been identified and described by Arrow (1962) as a process where labour learns through experience in the production phase. Learning takes place during activity—and it usually occurs through the attempt to solve a problem for which favourable responses are selected. The know-how to produce lies in individuals, production routines and practices, as well as experience, e.g. through trial-and-error or trainings. Over time learning yields increasing returns to scale both in gross investment and labour. Learning-by-doing, also covers the product design phase and the learning resulting in the redesign of products. Facilitating conditions identified as the most relevant for learning-by-doing in the development of energy efficient windows are listed in Table 1.

Learning-by-using, i.e. the producer of technologies learns from the experience of users, has been recognised by Rosenberg (1982) as one of the major drivers for technology change. In innovation systems it translates to continuously improved technology-user feedback towards producers of technologies. Substantial improvements can however take time. To use the technology according to its function and to be able to suggest suitable system-adjustments, the users have to accept and become familiar with it. Based on Kamp et al. (2004) and Andersen and Lundvall (1988) we have identified two significant factors that facilitate learning-by-using (see Table 1).

Learning however does not only come about between users and producers (continuous one-way feedback loop), but also among various other actors and interfaces (Lundvall, 1988). Based on the user-producer approach, Lundvall (1988) describes **learning-by-interacting** through various perspectives; such as incentives for interaction at parties, flows and channels of information, non-economic relationships, as well as the evolution of relationships in time and space. Learning-by-interacting has also been recognised as the basis for incremental innovations (Andersen

and Lundvall, 1988). Interfaces among different actors, providing the diffusion of knowledge, are suggested to be an appropriate system performance indicator. Based on the innovation literature (Hughes, 1983; Lundvall, 1988, 1992; Nooteboom, 1992, 2001; Cohendet and Llerena, 1997; Kamp et al. (2004)) and the network-actor literature (Håkansson, 1987; Callon, et al. 1992; Carlsson and Stankiewicz, 1995; Williams et al., 2000), we found three conditions that are relevant in facilitating the process of learning-by-interacting for the development of energy efficient windows (see Table 1).

3. The development path of energy efficient windows—policy framework

Policy intervention for energy efficient windows in Sweden has evolved fairly slowly and been characterised by different measures over time (see Table 2).

The policy instruments have been developed to support both technology development and market development. Technology development has partly been supported by a continuous governmental R&D and partly by the building code of 1975, which set requirements directly on the energy performance of windows in new buildings. Until today, SBN 1975 has been the only regulative policy instrument, which was applied to set special requirements directly on the energy performance of windows. In 2010, the recast version of the EU directive on energy performance of buildings (2010/31/EU) introduced new requirements on energy performance of windows also in refurbishment projects.

Market development of energy efficient windows has been supported by various short-term subsidies during the period of 1975–1993, and later during 2004–2010. While the first phase of tax exemptions did not have any requirements on the level of

Table 2

The most relevant policy instruments related to energy efficient window development in Sweden (1945–2010).

Sources: EU Directives (2002/91/EC, 2010/31/EU); Swedish Building Codes (BABS 1945, SBN 1975, BFS 1988, BBR12, BBR16, BBR18); Swedish Ordinance on Housing Financing: SFS 1974:946; SFS 2003:1204; Boverket (2010); Energimyndigheten (2006); Energimyndigheten (2008); Energimyndigheten (2009b).

Period	Policy instruments	Description/requirements
1945	First building code in Sweden	Official standards for windows: standards for quality and design, but not for energy performance
1956–58	Subsidies—governmental loans	After the Suez-crisis newly built family-houses was targeted to install better performing three-paned windows
1975	R&D	After the oil crisis of 1973, research programs were launched for improved energy efficiency (on e.g. basic window physics, such as heat transmission and long-wave radiation)
1975	Building code (SBN 1975)	Concrete requirements for individual building components in specific climatic zones (north and south). For windows (including glazing, sash and frame) the requirement for U -value (U_w) was set at $2.0 \text{ W/m}^2 \text{ K}$ in both zones
1975–1993	Subsidies—tax exemptions	For refurbishment of the existing house stock and window replacements. The first tax relief was set for a period of two years; then it was extended in an ad-hoc manner by no more than 2–3 years at a time. Note, no requirements were applied on the level of energy performance of windows
1985	Swedish P-label	Technical quality label, which set a minimum requirement for all essential characteristics of windows
1988	Building code (BFS 1988)	Introduction of performance based building codes; the requirement for an average U -value (U_a) on the whole building envelope was set (for calculation method see BFS 1988). Hypothetically allowed even higher U -values for windows than had been outlined in SBN 1975
End of 1980s	R&D	Increasing funding for long-term university-based research project—often in cooperation with the window and glass industry
1992 and 1994	Technology procurement programme	The requirement for energy performance was set at $0.9 \text{ W/m}^2 \text{ K}$ in 1992, when no feasible solutions was developed, the requirement was raised to $1.0 \text{ W/m}^2 \text{ K}$ in the second round of the procurement (1994)
2000s	European CE-label	CE requirements were integrated into the P-label; including initial type testing and factory production control. CE-label can provide access to the EU market for Swedish windows
2004	Subsidies—tax exemptions	For replacement of windows with improved energy performance ($U \geq 1.2 \text{ W/m}^2 \text{ K}$)
2006	Building code (BBR 2006 or BBR12)	Based on the EU directive on energy performance of buildings (2006): minimum standards on the energy performance of new residential buildings: south $110 \text{ kWh/m}^2/\text{year}$, north $130 \text{ kWh/m}^2/\text{year}$. More stringent requirements on the whole building envelope ($U=0.5 \text{ W/m}^2 \text{ K}$) Alternatively, requirements for windows in smaller residential buildings ($< 100 \text{ m}^2$): $U_w \leq 1.3 \text{ W/m}^2 \text{ K}$
2006	Energy declaration	Based on the EU Directive (2002/91/EC), requiring a declaration on the energy performance of buildings, in effect from 2009
2006–2007	Energy labelling	Voluntary scheme. A–G scale, “A” indicates the most energy efficient windows ($0.9 \text{ W/m}^2 \text{ K}$) and “G” indicates the “less” energy efficient ones ($1.5 \text{ W/m}^2 \text{ K}$)
2007	Specification for the passive house standard	Voluntary scheme. Adaptation of the German passive house standard for Swedish climate ($U_w=0.9 \text{ W/m}^2 \text{ K}$)
2009	Building code (BBR16)	Revision of the required level of energy demand in different climatic zones and the extension of the number of zones to three; the requirement in the northernmost zone: $150 \text{ kWh/m}^2/\text{year}$. More stringent energy performance requirements in buildings which are heated up directly with electricity: south $55 \text{ kWh/m}^2/\text{year}$, “middle” $75 \text{ kWh/m}^2/\text{year}$ and the northernmost zone $95 \text{ kWh/m}^2/\text{year}$
2009	Revision of the specification of passive house standard	It is mentioned in the specification that with the following revisions, the aim is to make the requirements more stringent, i.e. $U_w=0.8 \text{ W/m}^2 \text{ K}$
2010	EU Directive	EU directive on energy performance of buildings was amended and the recast version (2010/31/EU) was published in May 2010. For the first time, the directive addresses the existing building stock. Amongst others, it requires much reduced energy use in both new and existing buildings in each climatic zone; in terms of windows, it requires member states to set minimum energy performance standards for windows when being replaced or retrofitted
2011	Building code (BBR19)	Recommendation for more stringent requirements for energy performance of buildings: south $90 \text{ kWh/m}^2/\text{year}$, “middle” $110 \text{ kWh/m}^2/\text{year}$ and the northernmost zone $130 \text{ kWh/m}^2/\text{year}$ (in force from 1st November 2011)

energy performance of windows, in the second phase a U -value of $1.2 \text{ W/m}^2 \text{ K}$ or lower has been required to be eligible for the exemption (SFS 2003:1204).

To enhance the development of innovative energy efficient windows, a Swedish technology procurement programme was introduced in 1992. The requirement for the energy performance of windows was set at $1.0 \text{ W/m}^2 \text{ K}$. In the procurement process many actors were involved and it also supported market development through additional policy interventions, including information programs, seminars, exhibitions, education and campaigns for energy efficient windows.

In the 2000s, a number of voluntary approaches were introduced to drive technology and market development. In 2006, following the energy labelling of white products an “A to G scheme” was introduced for windows, whereby the best performing products had to have a U -value of $0.9 \text{ W/m}^2 \text{ K}$ or lower. In 2007, based on the voluntary passive house standard in Germany, a passive house specification was issued in Sweden, which was then revised in 2009 (Energimyndigheten, 2009b). These houses require “A” labelled windows ($0.9 \text{ W/m}^2 \text{ K}$) to be approved by an accredited test laboratory.

4. The development path of energy efficient windows—technology and market

The development and diffusion of energy efficient windows has been supported by various policy instruments; aimed to drive improvement of window technologies and increase in market share of energy efficient windows. Moreover, policy has contributed to the development of the Swedish windows industry. Below we describe the policy instruments applied and development the technology and the market in detail.

4.1. Early technology development

The continuous development of U -values has mainly been due to gradual technology development in the field of (a) window structures (frames, sashes and mounting) and (b) window panes (glazing and coatings). Fig. 1 shows the development of U -values in relation to the main developments of window technologies. Due to the Swedish climate, single-pane windows have been replaced by better insulating solutions already in the 17th century, e.g. by mounted/hinged sashes on the inner side of the

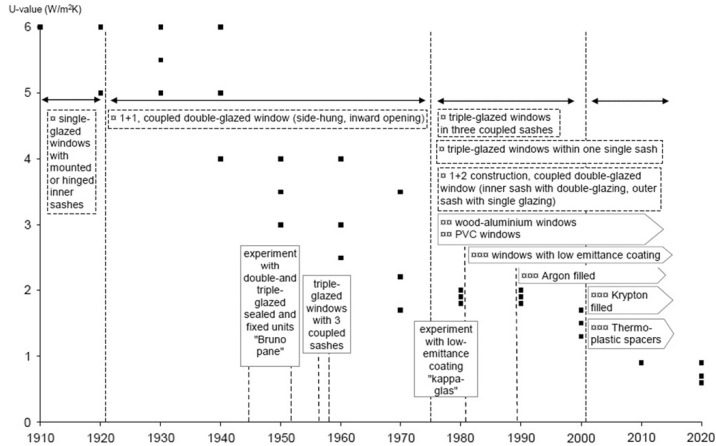


Fig. 1. Development of U -values and window technologies between 1910 and 2020. The presentation of U -values over time is based on literature, interviews with windows manufacturers and other professionals in or related to the industry.

window frame. In 1889, the coupled double-pane sash was patented, and from the 1910s to 1920s double-pane replaced single-pane sashes and remained standard until 1970s. In the 1940s and 1950s, insulated glass units (IGU)¹ appeared in the form of double-glazed and triple-glazed sealed and fixed sashes (Bruno-pane) in houses designed by Bruno Mathsson, furniture designer and architect, as well as in some newly built family-houses (Böhn-Jullander, 1992, 2003). With the introduction of double-pane windows, the U -value halved from 6.0 to 3.0 $W/m^2 K$, and thus the thermal performance of windows increased with an average of 100%. In the 1950s, single-family houses also benefited from a short-term governmental loan, which was given after the Suez-crisis and resulted in the installation of triple-pane windows with a U -value of 2.0 $W/m^2 K$, coupled in three sashes.

4.2. Technology development 1970–2010

In the 1970s, the first policy instruments were introduced to support technology development. By the mid 1970s, three different window structures were developed that could fulfil the requirements of the building code (SBN 1975) that called for a U -value of 2.0 $W/m^2 K$ for windows (see Fig. 2). In the late 1970s, and as a response to the oil crisis and stricter requirements, the glass industry took energy efficiency a step further by introducing low-emissivity glass coating.² This glass has a thin metallic coating, which reflects radiant heat back to its source, thus in winters the building is kept warm and in summers cool. This technological development is considered to be the greatest breakthrough in the flat glass industry that aims at increasing the energy conservation performance of windows. As building codes of the 1980s did not require windows with improved qualities,

the thermal performance of windows available on the market more or less stagnated until the end of 1990s (see Fig. 2).

The 1980s were characterised by the improvement of quality performance (Swedish P-label) and intense testing activities, including initial type testing and factory production control. The technology procurement programs of the mid 1990s required windows with a U -value of 1.0 $W/m^2 K$ and thus highly supported technology development. SP, the Technical Research Institute of Sweden assisted competing companies to meet the requirements of the procurement programme by providing methods and tools for U -value calculation and testing. The requirement was accomplished by triple glazing, two low-e coatings and a traditional wooden sash with argon or krypton gas fillings and traditional spacer materials between the panes (Energimyndigheten, 2006).

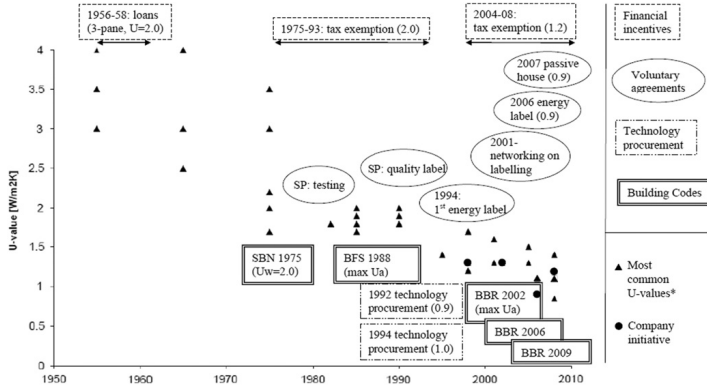
Over the years, window structures, glazing and mounting have developed from a simple technology to a more complex product. The latest glazing innovations include combined coatings for both solar control and energy efficiency and have very low emittance (Wall and Bülow-Hübe, 2001). Important design innovations include the distance between the panes, the proportion between the panes and the frame, the glazing systems, the various low conductivity gas fillings (e.g. vacuum, argon, krypton, xenon), the different spacers (e.g. metal, thermoplastic) in between the panes, the combination of wooden frames with alternative materials (such as plastic and polymers) and the airtight mounting. The U -values of the best available technologies today are in the range of 0.7–0.6 $W/m^2 K$. The energy label for windows (2006) and the stringent requirements of the voluntary passive house standard (first issued in 2007) highly contributes to the development and application of these technologies.

4.3. Market development 1970–2010

Due to several policy instruments, the market share of energy efficient windows has increased over the past 30 years, however slowly (see Fig. 3). Insulated glass units (IGU) and coupled three-pane sashes became competitive and excessively used by the end of the 1970s. By the end of the 1980s, 1+2 coupled double-panes and triple-panes windows were the most commonly sold window types (2.0 $W/m^2 K$). Low-e glass was commercially introduced to

¹ An insulating glass unit is a multi-glass combination consisting of two or more panes enclosing a hermetically sealed gap, which can either be air or a special gas, such as argon. The most important function of the IGU is to reduce thermal losses.

² Emissivity refers to an object's power to radiate heat, light, etc. In the flat glass industry, the term is used to measure the ability of window glass to control energy and minimise heat loss in cold weather. The lower a product's emissivity, the more energy efficient it is.



* Information on the most common U-values over time is based on interviews with window manufacturers and other professionals in or related to the window industry.

Fig. 2. Policy intervention for energy efficient windows in Sweden (1950–2010).

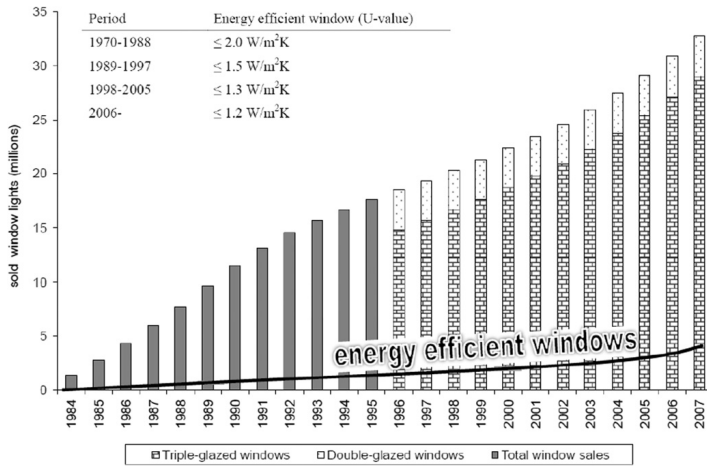


Fig. 3. Statistics on accumulated window sales and estimations on energy efficient windows share in Sweden (1984–2007).

the market in the beginning of the 1980s. SBN 1975 and short term subsidies between 1975 and 1993 supported the installation of better performing windows (i.e. better than the existing ones). Interviews indicate that the thermal performance of windows installed in the 1980s and the beginning of the 1990s were in the range of 1.5–1.8 W/m² K. The share of low-e coated windows does not show major increase however until the end of 1990s. In 1998, triple-pane windows with low-e coating and argon gas filling (1.3 W/m² K) were introduced as a company standard³ at one of the Swedish window manufacturers. It highly contributed to the

jump in sales of energy efficient windows. In 2000, approximately 56% of all the windows (including both triple- and double-glazing) sold in Sweden were coated with a low-emissivity layer (Bülow-Hübe, 2001). In 2008, one of the window manufacturers, representing 40% of market sales, introduced 1.2 W/m² K as a company standard, which supposedly led to an increasing market share of windows with U-values of 1.2 W/m² K. In 2007, 70–80% of total window sales had U-values 1.3 W/m² K or below, while the market share of windows with U-values of 1.2 W/m² K or lower was approximated to 50%.

³ By company standard meant that windows with U-value of 1.3 W/m² K are produced for stock in large volumes, any other client requests are handled individually according to the order specifications.

4.3.1. Structure of window industry

Due to the tradition of wooden framed windows in Scandinavia, window products were institutionally in the assortment of

Swedish joinery factories. By the 1970s, as a result of a general trend in many industries towards product and process specialisation, some of the joineries, instead of having a broad variety of products, concentrated merely on window manufacturing. By the 1990s, production process specialisation reached an extent where larger window producers started to outsource wooden sash and frame manufacturing to larger joineries and profiled themselves to window mounting. By the 2000s, two window manufacturers reached a combined market share of 70–80% and the remaining part of the market was represented by between ten and twenty smaller companies. The window industry went through a high level of specialisation in the past 30 years. Windows became complex products involving various actors, from joineries and glass producers to warm-edge spacer and cladding providers, in the production process. The specialisation to window mounting, mostly involving a couple of bigger manufacturers, led to increased productivity and higher production rates; while outsourcing ensured improved quality.

In contrast to the window manufacturing industry, the glass industry is highly globalised. There have been three main glass producers supplying window manufacturers with glass panes and since the beginning of the 1980s low-emissivity glass. Between 1990 and 2000, the sales of low-emissivity glass products grew from around 20% market share to an approximated 50%. The availability and later the wide supply of low-emissivity glass has resulted in increasing production of better performing windows.

The Swedish window market has classically been self-sufficient; bigger manufacturers have supplied the internal market, smaller businesses have specialized for export. A recent phenomenon is the appearance of low-prices import windows from Central Europe, which is likely to influence the future development of the Swedish market structure of energy efficient window supply and costs.

4.3.2. Price development

The consumer price (price paid by the end-user) of windows has been fairly stable until the 2000s. From the beginning of the 2000s, an increase of approximately 3–5% has been estimated by the interviewed window manufacturers; this price increase has also been reported in international window market studies (InterConnection, 2010; Freedonia Group, 2009).

According to interviewees, production costs of energy efficient windows (cost for window manufacturers to produce windows) have been decreasing slowly over the years. The average slow decrease is mainly due to the dynamics of the cost of window glazing. Today, the share of glazing cost stands for 20–25% of the consumer price.⁴ The cost of the glass used in window manufacturing decreased by half from 1970 to 2000 (Jakob, 2006); however, increasing oil prices⁵ has resulted in an estimated 60% increase in glass prices in the past ten years. In all, despite the radical fluctuation, the glass price was reduced since the 1970s.

The price of low-emissivity coated glazing has in average also decreased over time, despite the significant technical progress in terms of thermal performance in the last forty years. According to the interviewed window manufacturers, when low-e IGUs were introduced on the market at the end of the 1980s, they cost four times more than uncoated glazing, however the price started to slowly decrease by the introduction of standardized processes and increased production, the difference is estimated at 50% at the end of the 1990s, at 20% in 2003 and at 5–7% today.

⁴ The consumer price windows consist of the following main cost items: 1/3 labour&other, 2/3 material. The material cost can be divided into three categories: 1/3 glass, 1/3 wood and 1/3 fittings&mounting.

⁵ Glass production, i.e. sand melting is a highly energy intensive process.

Further developments are expected from the window frame manufacturing processes in the advancement of the thermal performance of window frames and sashes. Attempts have already been made to improve the performance of window frames; however as Jakob and Madlener (2004) and Jakob (2006) shows even small improvements result in great price increases, especially in the case of wooden-framed windows, which might further limit energy efficient windows to ride down the learning curve.

5. Analysis and discussion: essential paths of learning

As described above, policy intervention has resulted in technology development, market development, as well as contributed to industry development and cost/price reductions. One of the main contributing factors to this is that the policy instruments applied have facilitated and supported various learning processes. In this section we present the analysis of the role of learning processes. By applying the framework presented in Table 1, we identify the relevant conditions for learning-by-searching, learning-by-doing, learning-by-using and learning-by-interacting and assess whether and how various policy instruments have been addressing and/or supporting these underlying conditions for learning. The overall results are presented in Table 3; the more detailed results are presented in the text below.

5.1. The support of learning-by-searching

Learning-by-searching, through direction of search and development, has been supported by regulations and standards; i.e. as of the 1970s Swedish building codes and national and international standards for glasses and windows. Since 1985, the P-label, a Swedish technical quality label, and the CE-label, an international quality label, set the minimum requirement for all essential characteristics of windows. Directions have also been provided through the technology procurement programme of the 1990s. This programme required energy efficient windows with an U -value of 1.0 W/m² K; windows that were not yet on the market. Although these energy efficient windows, partly due to the

Table 3
The influence of different policy instruments on various learning processes.

Policy instruments	Learning-by-searching	Learning-by-doing	Learning-by-using	Learning-by-interacting
R&D	+			
Building codes	+			
Standards (e.g. P-label, CE-label)	+			(+)
Technology procurement programme	+	+	+	+
Subsidies				
w/o energy performance requirements		(+)	+	
With energy performance requirements	+	(+)	+	
Passive house standard	+		+	+
Voluntary energy labelling (information)	+		+	+
Testing and certification		+		+
Education and trainings	+	+		+

+ direct influence; (+) indirect influence.

building recession in 1992–1998, did not gain a large market share until the beginning of the 2000s; through the procurement it was proved that the development of these windows is technically and economically feasible. In recent years tax-exemptions schemes with specific performance requirements and voluntary standards, such as the passive-house concept and labelling schemes, have further directed and challenged the development of learning-by-searching.

Learning-by-searching has also been facilitated through (RD&D). Since the mid 1970s, governmental RD&D has supported the development of new knowledge and competences related to more advanced windows. The development of scientific knowledge and theory in basic window physics, e.g. heat transmission and long-wave radiation, has facilitated learning-by-searching and resulted in important and fundamental improvements in window structures and more importantly glazing.

In addition to research supported by the government, window manufacturers have played an important role in supporting learning-by-searching. Privately financed R&D departments were found at larger window manufacturers already in the early 1970s. As a result of intensive R&D activities, one Swedish company developed and offered quadruple-pane windows to its customers already in the 1970s. Since 1980s, most window companies have had their own product development departments; and in 2000s window manufacturers started to set aside even more resources for research and development. Today, approximately 1% of a larger window manufacturer's turnover is earmarked for energy efficiency developments, which largely includes costs and expenditures on internal and external staff involved in R&D activities as well as modelling and testing activities.

Learning-by-searching has also been guided by patents and reports on the development of different parts of windows since the end of the 19th century. Insulated glass units were patented in the United States in 1865 (Wolf, 1988) and as Bruno-panes, part of a building technology in Sweden in the 1950s (Böhn-Jullander, 2003). Solar control and low-emissivity glazing for luxury railway cars existed from the early 1960s, and since the beginning of the 1980s, an immense quantity of patents and reports comprising low-e coatings has been published (Gläser, 2008).

5.2. The support of learning-by-doing

Early experiences in the production of windows, as of the 1900s, resulted in important learning-by-doing. The introduction of certain policy instruments for energy efficient windows enhanced this learning by facilitating the conditions for learning-by-doing as well as some improvements related to the design, the performance and the production processes of windows. A major improvement was achieved when one of the largest manufacturers changed the production chain from clear triple-pane windows to IGUs with low-emissivity coating in 1998. This also resulted in notable consumer price reductions for standard windows.

Testing and certification processes have provided important support learning-by-doing. Testing new types of windows is, however, a costly, complex and time consuming procedure. To facilitate testing SP, the Technical Research Institute of Sweden has coordinated various types of testing activities since the 1970s. As of the end of the 1990s, SP introduced the "hotbox method" for physical window testing by establishing the only standardized physical window testing facility in the country. Through the hotbox method, different physical circumstances can be created for testing various features of windows, complementing the modelling calculations. Testing was also a key process within the technology procurement programme.

Education, another facilitator of learning-by-doing, has also been supported by the glass industry; since the 1970s, glass suppliers have been holding informational trainings and seminars on development of different glazings, coatings and glass' performance, especially when glass products with new characteristics entered the market. These trainings have been company and product specific, based on the previously established relationship between window manufacturers (buyers) and glass manufacturers (suppliers).

The most crucial partner supporting learning-by-doing may be SP, the Technical Research Institute of Sweden. In the 1980s, SP provided some courses on thermal performance calculation modelling mostly to large window manufacturers that particularly requested these trainings. The technology procurement programme, where SP assisted the participants in calculating U -values and modelling window performance, established the scenery for extensive educational and consulting activities on energy performance modelling for windows. By beginning of the 2000s, SP trainings became popular. The courses were conducted on technical issues, such as heat flux and factors influencing the thermal performance of windows, and partly on how to manage the different two and three-dimensional heat flow modelling tools. The activities at SP have heavily contributed to learning-by-doing in terms of skill and experience development of various actors.

Indirectly, learning-by-doing has been supported through policy incentives that have led to an increase in demand and thus an increase in production of energy efficient windows, such incentives have included various subsidies, tax exemptions and short-term loans. In general, these incentives supported essential learning-by-doing. However, the short-term approach of these financial incentives may have jeopardised long-term investments in the industry and could have limited cost reductions of energy efficient windows.

5.3. The support of learning-by-using

Learning-by-using can be supported through active involvement of users; moreover, it can result in important feedback to production and product design. Adequate and continuous contacts between producers and users can result in both learning-by-using and learning-by-doing.

In Sweden, learning-by-using energy efficient windows have been supported by subsidies, loans and tax reduction programs provided since the 1950s. In combination with labels and voluntary standards of the 2000s, these incentives have strongly supported market demand and learning-by-using.

Learning between producers and users has been limited. The end-users of window products are fragmented and disperse. Window manufacturers have in general very little direct contact with the end-users of their products. Genuine contacts have rather been developed with large building companies, house manufacturers, building material stores and wholesalers as well as property and house management companies. End-users and their experience in using the windows have, as a rule, been unknown for the window manufacturers. In general, contacts between end-users and window manufacturers are channelled and articulated through the building companies, house manufacturers and property and house management companies. With regards to energy efficiency, the end-users (or intermediate companies) have mostly reported complaints on for example aesthetics, humidity, maintenance, air tightness and condensation. Slight differences in the communication however have been observed; in general, larger building companies, having an intermediary role between end-users and window producers have been lagging behind in terms of ordering windows with higher energy

efficiency performance, whilst house manufacturers, having more direct contact with the end-users, have been more concerned not only about the overall energy performance of the final product being delivered, but also the performance, comfort and aesthetics of the individual building components, such as windows. In all, the structure of the market jeopardises that vital information from the end-users can be lost on the way towards the producers, and vice versa. The non-correlation between end-users of window manufacturers has put obstacles in the way for important processes of learning-by-using and learning-by-doing.

To improve essential feedback loops a few projects have been developed by window manufacturers where reference groups, including procurers, authority experts, product developers and architects, have been asked to support feasible and legally acceptable window solutions. Since the 1990s, larger companies carry out client surveys on a regular basis, lately including also energy efficiency issues. However, window manufacturers in general do not have established feedback procedures with customers or end-users. Contacts are often problem-based and initiated by end-users. Sporadic feedback is provided to the window manufacturers specifically in refurbishment processes and due to bad experience. The low intensity and irregularity of feedback mechanisms between end-users and producers has significantly slowed down learning-by-using as well as learning-by-doing.

Another innovative process, actively involving users, was the technology procurement programme; this by creating an active buyer group with actual demand and thus supporting learning-by-using. The group was involved in setting the requirements of the specification, which facilitated the communication of end-users' demand towards producers in the development phase. Interviews indicate that the energy efficiency label, which was introduced in the frame of the programme, raised awareness on energy efficient windows among consumers.

In recent years learning-by-using has been supported by the development of voluntary standards, such as the passive house concept. The specification of the standard was set by the property owners taking into consideration both the feedback from end-users and the results of the performance monitoring.

5.4. The support of learning-by-interacting

Learning-by-interacting is based on actors' involvement, interaction and networking, as well as enhanced by mutual interest and change agents.

The first attempt by the government to support a wider collaboration and interaction of actors was initiated through the procurement process, this programme involved actors, such as architects, building companies, window manufacturers, flat glass producers, the testing institute (SP) and national authorities. The programme generated the first broad-scale dialogues on how to realise highly performing windows with improved U -values. The activities included in the procurement programme (testing, educations, etc.) generated regular contacts and intense discussions between window producers and the testing institute, as well as resulted in continuously improved prototypes and thus windows with increasingly better thermal performance.

In the 2000s, European collaboration on window energy rating together with the EU Directive on Energy Efficiency in Buildings (2002/91/EC) provided an essential basis for the development of energy labelling of windows. The number of interested parties has been continuously increasing, between 2006 and 2009 from eleven to fourteen window manufacturers; participants represent 85% of the Swedish window sales market. The EU Building directive and the labelling scheme have not only contributed to the evolving collaboration among window manufacturers but also

interaction with authorities. Since 2000, the Swedish Energy Agency also keeps records on windows with U -values of $1.2 \text{ W/m}^2 \text{ K}$ or lower; the list in collaboration with window manufacturers is continuously updated. In 2000, there were 47 products registered, today the number of listed windows is 247 from 35 manufacturers (Energimyndigheten, 2009a). The voluntary building standard of e.g. passive houses is also a product of interaction between actors.

To support learning-by-interacting by governmental incentives is a fairly recent phenomenon in the development of energy efficient windows. However, interactions among industry actors have taken place on different levels and to different extent for years. Since the beginning of the 2000s, mutual interest brings window manufacturers together at the Swedish Federation of Wood and Furniture Industry (TMF)⁶, which provides a meeting platform for wooden framed window manufacturers. In the frame of the yearly three to four meetings common problems are addressed, possible solutions are discussed and common points of views are formulated. The mutual trust among window manufacturers has been growing since a common understanding was established on the meaning of energy efficiency indicators and the use and interpretation of U -values. Creating a common language among window manufacturers, contributed to the development of mutual trust and thus facilitated learning-by-interacting.

Learning-by-interacting was further supported through training and education programs coordinated by the glass industry. The interaction was initiated and well-maintained by the few glass suppliers mainly driven by their interest of marketing their (new) products.

6. Conclusions

The study shows that various policy incentives have facilitated important processes of learning, in turn, these learning processes supported technology improvements and market diffusion. As a result, best available technology improved from $1.8 \text{ W/m}^2 \text{ K}$ in the 1970s to $0.7\text{--}0.6 \text{ W/m}^2 \text{ K}$ in 2010, in the same time period the market share of energy efficient windows increased from 20% in 1970 (average U -value of $2.0 \text{ W/m}^2 \text{ K}$) to 80–85% in 2010 (average U -value of $1.3\text{--}1.2 \text{ W/m}^2 \text{ K}$).

In all, this study has provided some insights in how different policy instruments have been facilitating important learning processes. In the case of learning-by-searching, both public and private R&D as well as regulations and standards have been essential. The building code of 1975 required a U -value of $2.0 \text{ W/m}^2 \text{ K}$, which assured that newly installed windows should have at least triple-glazing already in the 1970s. The building codes since 1988, have, however, not set any specific requirements on windows. Since then learning-by-searching has been guided mainly by performance requirements set in the tax exemptions and voluntary approaches, such as the voluntary labelling schemes and the passive house concept.

Learning has also been supported by the increase in demand—both in terms of learning-by-doing and learning-by-using. Essential incentives for this have been various subsidies, tax exemptions and short-term loans. However, the short-term approach of these may have jeopardised long-term investments in industry and may have limited cost reductions of energy efficient windows. The analysis shows fairly stable consumer

⁶ TMF (Trä- och Möbelindustriförbundet) is the National Trade and Employers' Association of the Wood Processing and Furniture Industry in Sweden. Since 1996, SNIRI (Snickeriernas Riksförbund), the National Association of the Swedish Joinery Factories, having most of the window manufacturers as its members, is a part of TMF.

prices for conventional windows over time, while prices for energy efficient windows show a slight decrease approaching the price level of conventional windows. This study indicates that factors, such as immense increase of glass prices in the past ten years and the highly concentrated market structure of the glass industry seems to have had a larger influence on the consumer price development than the learning processes.

An incentive that supported learning in all four dimensions was the technology procurement programme of the 1990s. Learning-by-searching was supported by the strong requirements set by the buyers; learning-by-doing was supported by the testing activities; learning-by-using was supported through the active buyer groups; and learning-by-interaction was supported by the interactive art of the programme that pulled together actors, such as architects, building companies, window manufacturers, flat glass producers, SP and national authorities. The programme generated the first broad-scale dialogues on how to realise highly performing windows with improved U-values, and as a result, larger companies came to use reference groups enhancing users' demand and feedback processes later on. Moreover, the technology procurement programme resulted in more frequent use of testing facilities and also established a mutual interest for education and training activities.

In the early 2000s, EU initiatives grounded the mutual interest on creating a common language among window manufacturers and a common understanding of the energy efficiency performance of the products in Europe. In 2006, based on the EU Directive on Energy Efficiency in Buildings (2002/91/EC) three Nordic countries started a pilot project on energy-labelling of windows. Today, almost 250 windows are involved in the energy-labelling project produced by companies representing 85% of the market. The voluntary buildings standards of e.g. passive houses are also a product of interaction between actors and thus provided through learning-by-interaction.

In all, this analysis shows how various policy initiatives support different learning and that a mix of learning processes is needed for technology change and market diffusion.

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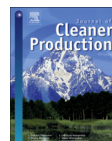
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The role of policy instruments in supporting the development of mineral wool insulation in Germany, Sweden and the United Kingdom

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ABSTRACT

The objective of this study has been to analyze the introduction and development of mineral wool building insulation in Germany, Sweden and the UK, and to examine the policy instruments that support these processes. The aim has been to improve our understanding of the role of the policy instruments. The analysis focuses on the development of the policy framework, the development of technology, the interaction among actors involved, the formation of networks and key learning processes regarding the development and diffusion of mineral wool insulation. The results show that private and, to some extent, public R&D and testing processes have formed the basis of technology development. Over time, successively progressive building codes and voluntary standards have come to be key drivers of the development of mineral wool building insulation. Since the beginning of the 2000s, these policy instruments have also been a main driver of the interactions among actors. Financial incentives and information have been crucial for learning and the development of knowledge in building renovations.

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1. Introduction

The building sector accounts for almost 40% of the total energy use worldwide (Laustsen, 2008; McKinsey, 2009). Improvements in the building envelope can reduce heating demand by a factor of between two and four, and a factor of eight can be achieved when other measures are included (Demirbilek et al., 2000; Ürge-Vorsatz et al., 2007). Various energy and environmental policy instruments, such as building standards, subsidies and information programmes, have been introduced since the 1970s, with the aim of achieving these potential savings. It is necessary to use assessment of different types in order to better understand the impact of such policy instruments and to provide insights into the effects of technology change. This study analyzes the development and introduction of insulation materials – both in terms of better performance and broader market uptake – since the 1970s. The study applies a theoretical framework that describes changes in the innovation system, and highlights how various learning processes have been supported by different policy instruments.

The study analyzes the technology and market development of mineral wool building insulation in Germany, in Sweden and in the UK. These countries were selected because their policy landscapes

are historically different, while market development has been fairly similar. The stringent Swedish insulation standards have served as a model in Europe since the 1960s, while Germany and the UK are currently leaders in promoting energy efficiency in buildings. Germany has not only periodically strengthened building codes but also focused on targeted financial incentives to promote energy efficiency. The UK started to focus on energy efficiency policies as recently as fifteen years ago, and provides valuable lessons in the implementation of financial incentives.

The overall purpose of this study is to improve our understanding of the role of policy instruments, in particular, how they have (or have not) supported the development and diffusion of mineral wool products. Based on the concept of sectoral innovation system (Section 2) of mineral wool insulation, we analyze the development and the role of the policy framework (Section 3) in terms of the development of technology (Sub-section 4.1), the development of interactions among actors and networks (Sub-section 4.2) and different learning processes (Sub-section 4.3). In all, the study assesses and presents the impact of various policy instruments on relevant elements of the innovation system (Section 5).

2. Conceptual and methodological framework

Theories of innovation systems have been developed and used to various extents to assess the impact of energy policies during the past three decades (see, for example, Freeman, 1988; Lundvall,

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1988; Nelson and Winter, 1977; Nelson and Rosenberg, 1993; Carlsson and Stankiewicz, 1995; Carlsson and Jacobsson, 1997; Edquist, 1997; Bergek et al., 2008; Jacobsson and Bergek, 2011). These theories describe an innovation system as a purposeful set of elements that interact with each other through ubiquitous processes of creation and the diffusion of artifacts and knowledge (see, for example, Lundvall, 1992). Theories of innovation systems differ in scope, and may describe national innovation systems (Freeman, 1988; Lundvall, 1988, 1992), regional innovation systems (Cooke, 1996), sectoral innovation systems (Breschi and Malerba, 1997; Malerba, 2004), or technological innovation systems (Carlsson and Stankiewicz, 1991, 1995). All theories, however, share certain features. All innovation systems are composed of *actors*, *networks* and *institutions*. The sectoral innovation system (SIS) approach further characterizes the systems in terms of their differences in *technology*, *knowledge base* and *learning process* (see, for example, Nelson and Winter, 1982; Malerba and Orsenigo, 1996; Malerba, 2002, 2004).

Learning is one of the most important drivers of technology change (see, for example, Arrow, 1962; Rosenberg, 1982; Nelson, 1995; Dosi, 1997; Edquist, 1997; Metcalfe, 1998; Kamp et al., 2004; Jensen et al., 2007; Lundvall, 2007). "Learning" is a broad concept and several processes of learning have been identified over time (see, for example, Arrow, 1962; Rosenberg, 1982; Lundvall, 1988; Garud, 1997; Kamp et al., 2004). Learning is considered to be a key process in the formation of the innovation system and a process by which new or existing knowledge, skills and experience are developed. Institutions can subsequently be established on the knowledge base built up in this way. Further, networks of actors can be built when such knowledge is exchanged, and technologies and markets can advance through the development of the knowledge.

The conceptual framework of this paper is based on the sectoral innovation system (SIS) approach developed by Malerba (2002, 2004). We use the SIS approach to assess the policy instruments that support the development and diffusion of mineral wool insulation in Germany, Sweden and the UK. This analysis captures *technologies (products)*, *actors (agents)*, *networks (interactions)*, *institutions (policy instruments)*, and *knowledge and learning processes* of innovation systems (Malerba, 2002).² The SIS approach is used to describe the national nature of policy frameworks and the international nature of the insulation market.

This study assesses the development of the *technology* by examining such factors as: a) the *direction of search and development*, b) *research & development (R&D)*, c) the management of *new knowledge*, and d) *testing* (Table 1). These factors are chosen as they are also relevant conditions for learning (see, for example, Nelson and Winter, 1977, 1982; Kamp et al., 2004).

Actors and *networks* are characterized as individuals (such as consumers, end-users, researchers and policy makers), business entities (for example manufacturers and suppliers), non-business entities (for example universities, banks and authorities), organizations (including sub-units), and groups of organizations (for example industry associations). The analysis of actors and networks, based on Malerba (2002), focuses on insulation manufacturers and highlights the following factors: a) the *sophistication of the user group*, b) *forms of interaction*, and c) the *proximity and mutual interests* of actors and networks (Table 1). These factors are also relevant conditions for learning (see, for example, Rosenberg, 1982; Garud, 1997; Kamp et al., 2004).

Policy instruments are considered as institutions, in this study, which are characterized as norms, standards, rules, laws and similar constructs that shape and regulate the actions of actors and the interactions between them (Lundvall, 1992; Malerba, 2004). In order to assess the role of policy instruments in the development and diffusion of mineral wool insulation, we will here consider only policy instruments and no other institutions (Table 1).³

The analysis of the development of technology and development of actors and their interactions requires also discussions about the *development of knowledge* (Malerba, 2002), in terms of accessibility (internal and external) and cumulativeness (learning processes and feedback loops).⁴ *Learning processes* will be analyzed in terms of learning-by-searching, learning-by-doing, learning-by-using and learning-by-interacting. *Learning-by-searching* or *learning-by-studying* (Garud, 1997) can be defined as organized knowledge acquisition, for instance, through R&D, universities and research institutes, embodied in various types of publications or prototypes (Kamp et al., 2004). *Learning-by-doing* takes place during an activity (for example production), where individuals learn through experience over time; it can yield increasing return of scale in investment and labor (Arrow, 1962). *Learning-by-using* often translates into continuous feedback-loops between technology-producers and technology-users (Rosenberg, 1982). *Learning-by-interacting* takes a broader perspective than learning-by-using, where not only producers learn from the experience of users, but also different actors learn from each other through various interfaces in economic and non-economic relationships (Lundvall, 1988). For more detailed description of the four learning processes and factors facilitating learning see Kamp et al. (2004) and Kiss and Neij (2011).

The framework that we apply provides an adequate basis on which to assess the role of policy instruments in the development of technology and in the development of actors and networks. It also allows us to examine the presence and intensity of some learning processes in innovation systems. We have identified also factors that facilitate innovation, and investigated the impact of policy instruments through a literature review of company documents, agency and consultancy reports, and scientific publications. We have also carried out interviews with insulation product developers, marketers and other representatives of the insulation industry (9 interviews), research institutes (2), authorities (2) and other professionals in the field (2).

3. Policy instruments for improved building insulation

The introduction and development of mineral wool insulation materials started at the beginning of 20th century and gained ground after the industrialization of the production process in the 1950–60s. Research and development were driven by investment from large insulation manufacturers. Government policies, such as building codes, economic and voluntary measures, as well as R&D funding, became important support for the development and diffusion of mineral wool insulation during the 1970s. The thermal performance of buildings and insulation measures were promoted to different extents by national policies (Sub-sections 3.1, 3.2 and 3.3), until the introduction of the EU Directive on Energy Performance of Buildings (EPBD) in 2002. As the revised EPBD (2010) forces member states to adopt a definition for very low-energy

² The processes of competition (generation of variety) and selection are not included in this study (Malerba, 2002).

³ Other institutions, such as habits, routines, practices, for example patenting or user involvement in product development, are taken up as constructs facilitating technology development and/or interaction among actors, but have not been extensively addressed.

⁴ Organizational capabilities are not included in this study (Malerba, 2002).

Table 1
Framework for assessing the role of policy instruments supporting the development of technology and actor-networks as well as four learning processes.

Policy instruments:	R&D/	EPBD/	Building codes/	Labels/	Financial incentives/	Information/	Voluntary standards/	Testing/	Education & training
Technology development	a) Direction of search and development								Learning-by-searching
	b) R&D resources								Learning-by-searching
	c) Management of new knowledge								Learning-by-doing
	d) Testing								Learning-by-using
Actors and networks development	a) Sophisticated user group								Learning-by-using
	b) Form of producer–user interaction								Learning-by-interacting
	c) Proximity & mutual interest of actors and networks								

standards for new and existing buildings and to ensure that all newly constructed buildings comply with this definition by 2020, it has come to play a significant role in setting a framework with common goals for the international mineral wool insulation market.

3.1. Germany

Germany has a long history of addressing energy efficiency in buildings through various policy measures (Appendix 1). These include building regulations on heating and energy-saving measures introduced in the 1970s, financial incentives that involve KfW (the German Reconstruction Bank) introduced in the 1980s, and voluntary standards for energy-efficient houses introduced in the 1990s. Energy efficiency requirements laid down by regulatory instruments were strengthened at various times between 1977 and 2009, and each upgrade required approximately 30% better energy performance (IEA, 2008b). These upgrades have resulted in the energy demand for heating in new buildings falling from approximately 170 kWh/m²y to less than 40 kWh/m²y during the past 30 years (Fig. 1). The demand for heating energy decreased by about 30% between 1977 and 1995 in Germany (Geller et al., 2006). The major part of this decrease, however, was due to improvements in heating systems rather than to improvements in building insulation (BMVBS, 2007). The merge of the Heating Ordinance and the Energy Saving Ordinance (EnEV) in 2002 triggered further improvements in the building envelope, and seemed to result in an increase in insulation thickness (Fig. 2). Regulatory measures have been supported by KfW funds since the 1980s (Appendix 1).

The voluntary passive house standard, which was introduced as an addition to regulatory and economic instruments, posed much higher energy efficiency requirements than legislation. This standard called for the use of either thicker insulation (300–600 mm) or more innovative, thinner insulation materials with lower *U*-values⁵ (BMW, 2008). It was promoted and supported by additional incentives, including funding programmes (KfW bank), awareness-raising campaigns, demonstration projects (DENA), and a “Certified Passive House Designer” training programme (Passiv-Haus Institute).

One third of research and development funding in Germany originates from the government, and two-thirds from the private sector (BBF, 2008). The IEA (2009) has estimated that the total public expenditure for R&D on energy efficiency in buildings was around EUR 22.5 million⁶ in 2009. Funds were allocated to

programmes such as *Future Building* and *Research for Energy-optimized Construction* (BMW, 2007, 2009).

3.2. Sweden

In Sweden, building codes have stimulated the installation of higher performance insulation materials since the 1940s, Appendix 2. The first building code (1946) not only established quality standards for insulation materials, but also stipulated that installers should be properly trained. Energy efficiency requirements, however, were not considered until 1960. Increases in oil prices provided a strong incentive not only for energy efficiency, but also for fuel substitution. The building code, “SBN75” placed more stringent requirements on insulation, and these requirements contributed to improving energy performance in buildings until the end of the 1980s (see, for example, Nässén and Holmberg, 2005). However, a dramatic fall in oil prices (1985–1988), government investment in power production, government support for district heating systems, and the promotion of oil substitution by electricity all limited the stringency and implementation of energy efficiency measures in the building sector (Nässén and Holmberg, 2005). Requirements that had been defined as prescriptive measures (addressing individual building elements) were changed to performance-based measures following the adoption of the EPBD in 2002 (Table 2). Interviews have shown that performance-based building codes have been perceived as failing to lead to more efficient energy use in buildings in Sweden.

Subsidies have been available to complement the building codes and to increase energy efficiency in buildings since 1983. Special focus was placed onto installing improved insulation between 1983 and 1987. Interviews have shown, however, that these subsidies did not increase sales of insulation materials.

Voluntary instruments, such as the *Passive House Initiative*, have only recently started to shape the Swedish policy arena. The specification for the *Swedish Passive House* standard, which requires a *U*-value of 0.1 W/m²K for insulation, was published in 2007. This value can be achieved by using either thick insulation material or thin insulation material with a higher performance. The passive houses created during this initiative may, at first sight, appear to be new solutions on the market, but the rate of diffusion has been very low.

The Swedish Energy Agency has supported the provision of free advice on energy efficiency issues through local energy advisors since 1998. Insulation measures are among the three most frequently asked about technical topics in relation to energy efficiency (Khan, 2006).

Governmental expenditure in Sweden on research and development in energy use in the built environment has focused on heating and building services systems. Approximately two-thirds of

⁵ The *U*-value of a surface measures its thermal performance by giving the heat flux (Watt) through unit surface area (m²) at a temperature difference of 1 K or °C.

⁶ USD 31.6 million. Exchange rate: 1 USD = 0.71096 EUR (<http://www.oanda.com/currency/converter/>), 29 March 2011.

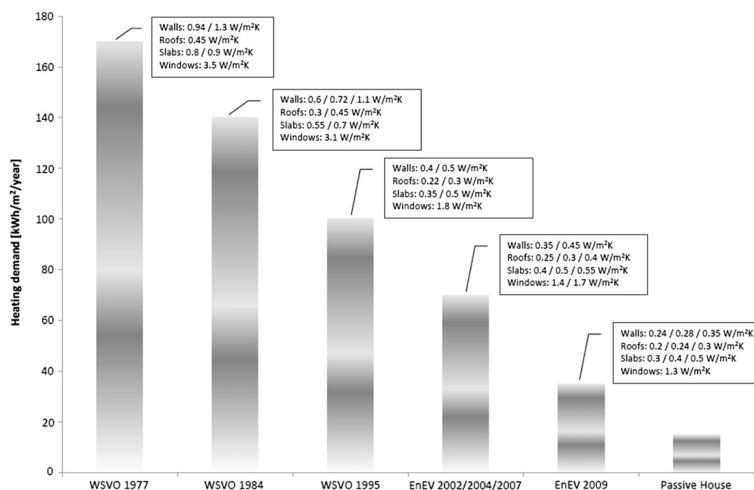


Fig. 1. Energy efficiency requirements and their impact (heat demand and U-values of building components) in Germany (1977–2009). Sources: WSV0 1977, 1984, 1995; EnEV 2002, 2004, 2007, 2009; Passive House Standard, and Witt, 2008 (modified).

the public resources for energy-related building research come from the Swedish Energy Agency. The agency has invested a total of EUR 122 million into this area since 1998, while the EU has invested a further estimated EUR 200 million in public and semi-public funding (Jansson et al., 2012).

3.3. United Kingdom

The UK energy efficiency policy arena has been characterized since the 1970s mainly by various types of economic incentives targeted at private households. Energy companies have played a more prominent role since the mid 1990s, and a special focus has

been placed on vulnerable households since the 2000s, Appendix 3. These incentives have been supported by the supply of information by advisory centers.

Government grants for improving energy efficiency in existing homes have been available through different schemes and for different target groups since 1978. These schemes include the *Home Insulation Scheme* (1978–1990), which is worthy of note since it led to a significant increase in the installation of insulation (Shorrock and Utley, 2003). Another scheme worthy of note is the *Pay As You Save* scheme (2009–2011), by which solid wall insulation was installed as one of the main energy efficiency measures in the 500 homes that participated (UK Green Building Council, 2009). It is also notable that most of the energy-savings targets set by schemes for energy suppliers (EESoP, EEC1, EEC2 and CERT) have been achieved through insulation measures (Fig. 3).

Building regulations for England and Wales⁷ that addressed energy efficiency issues were late arriving on the agenda, and were only modestly revised. Regulations introduced between 1965 and 2005 required that thicker insulation be installed; Fig. 4 shows the approximate thickness of a typical glass wool product required by building regulations for new buildings. These building regulations have contributed to reducing the energy consumption of an average new dwelling by about two-thirds (Shorrock, 2005). In addition, experience has shown that the insulation requirements for new buildings have been adopted also in the renovation of the existing building stock (Shorrock, 2005).

Voluntary standards have only recently become important in the UK, following the announcement by the government that all new homes are to be zero-carbon by 2016. The most widely used

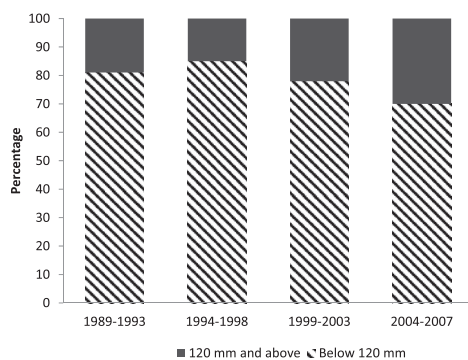


Fig. 2. Insulation thickness for external wall applications, 1989–2007 (based on BMVBS, 2007).

⁷ This section focuses on the building regulations in England and Wales. Scotland and Northern Ireland have different building regulations, which generally require the same standards. Regulations are, however, revised at different times in these countries.

Table 2

U-values for building components in Sweden (1967–2010) (Based on sources BABS1967, SBN1975, SBN88, BBR9, BBR10, BBR12, BBR16).

Revision year		Required U-values (W/m ² K)					
		1967	1975	1980	1988	2002 ^c	2006 ^d
Building components	Walls	0.40–0.80 ^a	0.25	0.25	Average U-value:	Average U-value:	0.18
	Roofs	0.35–40	0.17	0.17	$U_{m,krav} = 0.18 + 0.95 (A_f/A_{om})$	$U_{m,krav} = 0.16 + 0.81 (A_f/A_{om})$	0.13
	Windows	2.1–2.7 ^b	2.0	2.0	$A_f = \text{window area (m}^2\text{)}$	$A_f = \text{window area (m}^2\text{)}$	1.3
	Ground floors	0.40	0.30	0.30	$A_{om} = \text{total area (m}^2\text{)}$	$A_{om} = \text{total area (m}^2\text{)}$	0.15

^a 0.40 for light construction (<100 kg/m²) and 0.8 for heavy construction, such as brick walls.^b 2.1 when the window area is ≥60% of the wall area and 2.7 when window area is ≤60%.^c See detailed explanation of the calculation method in BBR10 (2002).^d Besides the calculation method for average U-values and the energy demand distinguished in three climate zones, there is an alternative requirement for the building components in small family houses (<100 m²).

building sustainability rating scheme in the UK, BREEAM, was introduced by the Building Research Establishment (BRE) in 1990. BRE has also played an important role in the introduction of regulations that stipulate higher levels of insulation, and in running an information programme on passive houses (PassivHausUK) (BRE, 2009). BRE and the Energy Savings Trust, together or separately, manage national information and capacity-building programmes. Evaluations carried out by the IEA, however, have shown that these programmes are not sufficient to support the implementation of building codes and extensive grants for energy efficiency measures (IEA, 2008a; 2008b).

Government R&D expenditure in the UK on energy efficiency in buildings is well below that of other OECD countries such as Germany. The IEA (2009) has estimated that the total expenditure for R&D in the UK was approximately EUR 5.8 million⁸ in 2008. It is also notable that no single authority has overall responsibility for R&D in energy programmes in the UK (IEA, 2009).

4. Development of the mineral wool insulation innovation system

Mineral wool accounts for approximately 60% of the European insulation market; the other major insulation materials are foamed plastics.⁹ Mineral wool has two competitive advantages: fire safety and sustainability performance. The interviews that we have carried out indicate that the market share of mineral wool insulation materials (measured as volume sold) has increased over time.

The market development¹⁰ of insulation materials has been promoted mainly by the stepwise tightening of building codes, financial incentives and voluntary standards (Section 3). Changes in building codes have been the main driver toward the increased use of insulation and toward the use of thicker insulation. In Germany, EnEV (2002) stimulated the introduction of glass wool insulation products of higher performance (lambda value = 0.035 W/mK),¹¹ and interviews show that the market share grew from 38.7% in 2005 to 45% in 2008. In both Germany (in the mid 1990s) and the UK (in the mid 2000s), financial incentives played a significant role

in further market development (see, for example, Shorrock and Utley, 2003; Shorrock, 2005). In Germany, the KfW programmes resulted in an increase of 37% in the percentage of buildings with insulation measures (ceiling, wall and floor) between 2005 and 2008 (BEI, 2009). In the UK, the ownership of cavity wall insulation rose from 2.4% (1974) to 32.3% (2001), and the ownership of loft insulation from 42.5% (1974) to 93.5% (2001) – this increase was closely correlated with the financial schemes in place from the mid 1990s (Shorrock and Utley, 2003). In Sweden, on the other hand, interviews indicate that the influence of financial incentives (which were available from the mid 1980s) was negligible in increasing the use of insulation. Voluntary standards, introduced in Germany in the 1990s and in Sweden and the UK in the 2000s, have affected mainly the diffusion of (new) energy-efficient insulation materials. The growing number of passive houses, more than 16,000 in Germany alone in 2011 (IPHA, 2011), has not only led to thicker insulation being used, but has also stimulated the development of new, thinner insulation materials.

The policy instruments applied have also contributed to the development of insulation technologies, changes in the actors of the innovation systems and interactions among them. They have also stimulated the development of knowledge and the learning processes in various ways.

4.1. Technology development of mineral wool insulation for buildings

Mineral wool insulation products, in the form of stone wool and glass wool,¹² and their production processes have developed over time, and this has occurred partly as a consequence of policy interaction. Mineral wool has been produced since the beginning of the 1900s and its initial development was mainly supported by private research and development. Since the 1970s, government policy interventions have come to complement private investment (Section 3), resulting in more intense improvements in the product and the processes. Consequently, the thermal performance of mineral wool products has improved by about 30% since the 1970s.¹³

⁸ USD 8.2 million. Exchange rate: 1 USD = 0.71096 EUR (<http://www.oanda.com/currency/converter/>), 29 March 2011.⁹ The main foamed plastic insulation materials are expanded polystyrene (EPS), extruded polystyrene (XPS), extruded polyethylene (XPE) and polyurethane/polyisocyanurate (PUR/PIR).¹⁰ In general, renovation (including repair & maintenance) represents the largest market for insulation, more than 60% of the total market in Germany, Sweden and the UK (BPIE, 2011).¹¹ The thermal conductivity or lambda value measures a material's ability to transmit heat at a given thickness measured as the heat amount in Watt per hour passing through a 1 m thick layer with a difference in temperature across the material of 1 K (or 1 °C). The unit is simplified as W/mK.¹² Glass wool and stone wool are interchangeable for many insulation applications. However, glass wool is favored for loft insulation due to its light weight and ease of handling, good thermal insulation and low cost, while stone wool is preferred for applications in which fire protection is important, due to its high melting point, which gives it higher fire resistance.¹³ Expert interviews show that the thermal conductivity values for mineral wool products improved from lambda values of 0.045 (W/mK) to the current 0.032 (W/mK) for glass wool products and 0.035 (W/mK) for stone wool. These improvements alone would not have been sufficient to achieve the energy efficiency levels required by building regulations. As a consequence, the thickness of insulation products had to be increased to achieve a specific thermal resistance* (which was also more cost-effective for the users). (*The thermal resistance (R-value) indicates a material's ability to resist the transfer of heat. It is affected by the thickness and thermal conductivity of the insulation: $R = t/\lambda$).

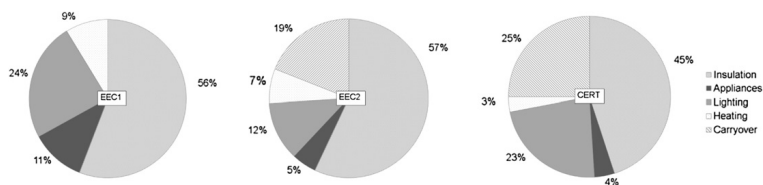


Fig. 3. Energy-savings (GWh) delivered under ECC1 (2002–2005), ECC2 (2005–2008) and CERT (2008–2011), based on Ofgem (2005, 2008, 2010).

4.1.1. Direction of search

In the 1930s, the technology development of mineral wool products required knowledge of *scientific theory* in such fields as chemistry and physics. The production was based on trial and error, rather than on scientific theory in engineering. The direction of search included the search for new raw materials, improvements in binders and in melting techniques, and the development of fiberization¹⁴ technologies, with the objective of producing finer fibers with improved thermal properties. New production technologies were developed as engineering knowledge grew, and these included new melting techniques for stone wool and new fiberization processes for glass wool. Production had become industrialized by the 1960s (Öhberg, 1987). Stringent *building standards* that defined the quality of insulation in terms of minimum insulation thickness and performance further stimulated the development of technology both in Germany (DIN 4108 from 1952) and in Sweden (BABS from 1960). The Swedish BABS 1960 also required that mineral wool materials be classified according to their lambda value. New fiberization technology for both stone and glass wool had been developed by the beginning of 1980s, giving lighter stone wool and more durable glass wool products. Products, with a thermal performance of 0.035 W/mK, entered the market in the 1980s, but market demand was low and they were sold in low quantities. These developments in products and process were supported by private R&D and led to increased production capacity during the 1980s and 1990s. Revision of building codes in the late 1980s opened the way for more flexible energy efficiency solutions, but the new codes were not stringent enough to stimulate further product development. Spinners with magnetic levitation bearings were introduced in the 2000s, which resulted in more evenly structured fibers and better thermal performance (Öhberg, 1987). This technical improvement not only made available flexible lightweight insulation materials that required approximately 60% less packaging space, it also had an effect on the development of knowledge in compression and logistics. This development has been driven partly by voluntary standards that promote low-energy buildings with special requirements for insulation. Voluntary standards have also been a key driver in the search for new high-performance insulation materials. In addition, (environmental) product specifications, such as the Environmental Product Declarations (EPDs) and the Green Guide to Specification (UK), served as *guideposts* for further product development.

4.1.2. Research & development (R&D) resources

Manufacturers of mineral wool insulation have invested heavily in R&D over the years, driven by the volatility of energy

prices and the search for ways to increase their competitive advantage. Accurate information about the evolution of R&D investment is not available, but we do know that private R&D is extremely important in the sector. One of the largest insulation manufacturers, for example, maintained its R&D budget during 2007–2009, while the budgets of other departments were cut due to the economic downturn. The continuous strengthening of building codes and an open dialog around the EPBD are good indicators for the insulation manufacturers to maintain R&D investments. R&D efforts have also been stimulated by various voluntary standards, such as the passive house standard (Germany, Sweden), the trend to zero-carbon buildings, and BREEAM certification (UK).

4.1.3. Management of new knowledge

Policy instruments have not had a direct influence on the management of new knowledge. Private R&D led to mature technology, products with low thermal conductivity, and high rates of production. This R&D gave increased experience and high levels of “internal” knowledge and specific know-how (such as knowledge in chemistry, physics, engineering and logistics). This knowledge has traditionally either been kept in-house or protected by *patents*. Large mineral wool manufacturers have generally used the protection offered by patents very actively. One of the largest mineral wool producers has claimed that patents not only give protection rights, but also stimulate improvements in energy performance. One of the largest mineral wool manufacturers, who registers a dozen patents each year protecting developments in the products’ thermal performance, has estimated that energy efficiency has improved by 25% during the past decade. Building codes and voluntary measures of the 2000s have supported process development and the launch of new insulation products, and have contributed indirectly to increasing the way in which new knowledge is managed – either as internal knowledge or as a resource that must be protected by patents. This study has not examined whether patenting contributes to or hinders the development of knowledge. Some interviewees, however, have stated that publicly available patent registers are a good source of information on the products and process development of competitors, and these registers contribute in this way to the development of internal knowledge.

4.1.4. Testing

Testing is a part of the production process and is a source of new and advanced internal knowledge. The CE Marking Directive (1995) and the CE label for insulation products (2003) established uniform standards throughout Europe, inducing more *frequent* testing of property products, a system of 3rd party inspection, and consistent reporting. The CE Marking Directive ensures credibility and facilitates the broader diffusion of mineral wool products within the EU. Energy efficiency requirements posed by voluntary codes also stimulate testing, and thus the development of

¹⁴ The molten glass is led through a series of channels to the spinning area where the glass flows by gravity into a rapidly rotating spinning device with fine holes. It is converted to fibers as it passes through the spinner.

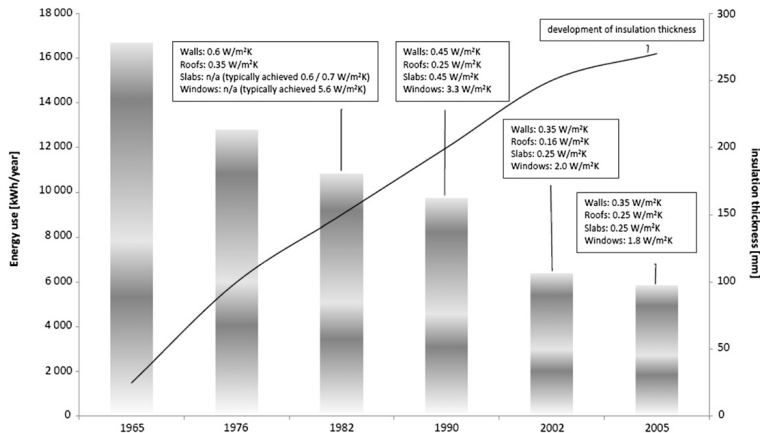


Fig. 4. Energy consumption in an average new dwelling built according to prevalent building standards (based on Shorrock (2005) and Defra (2008)), and the approximate thickness of a typical glass wool product for cold roof application (based on MacDonald, 2004) 1965–2005.

technology and knowledge. In Germany and in Sweden, the passive house standard requires certification that insulation products conform to quality assurance, stating that the certified building technology is “passive”. Testing is required before this certificate can be issued.

4.2. Market actors and networks

Actors and their interactions (through networks, for example) have developed with time, partly as a consequence of policy interventions. Market actors are plentiful in all countries examined (Germany, Sweden and the UK), and their roles are comparable. The supply chains for mineral wool insulation are similar, being in all cases fragmented. Technological, financial and know-how entry barriers¹⁵ are high, which has led to the European mineral wool market being highly consolidated and dominated by a handful of manufacturers (Isover, Knauf, Paroc, Rockwool, Saint-Gobain, Ursa). The main customers of insulation manufacturers are: a) distributors and building merchants, b) do-it-yourself (DIY) stores (which target mainly home-owners), and c) installers who work under private or public contracts. Most products are sold through distributors and building merchants, who sell the products to smaller merchants and/or to construction companies. End-users (building companies, sub-contracted installers and homeowners) are many links away from manufacturers. Utilities entered the scene in the UK when EEC programmes were introduced, and became the main customers of installers.

4.2.1. Sophistication of the user group

The fragmented supply chain and large distances between manufacturers and user groups such as building companies, sub-

contracted installers and homeowners leads to indirect demand formulation, mostly by intermediate actor groups, i.e. customers of manufacturers.

Financial incentives and voluntary standards have been used to increase the manufacturers’ consideration of user demand. Experience in the UK has shown how financial incentives stimulated insulation manufacturers to respond to demands from homeowners. Sales through DIY stores have increased since 2008, driven by increasing energy prices and the availability of governmental incentives. Loft insulation has been installed by homeowners or small installer companies. As a response, insulation manufacturers have adapted their product range such that it is more suitable for DIY users, and easier for them to install.

Voluntary standards have also played a significant role in the way in which certain user groups articulate increasing demands for energy-efficient products. German architects and designers who work with passive houses have expressed a strong interest in materials with lower thermal conductivity and thinner insulation meeting *U*-values of low-energy buildings. The impact of this trend on the insulation industry has, however, been low, since it affects mainly wall insulation. Further, low-energy buildings account for a low market share.

In addition, advisory centers were established in all three countries to stimulate interest in implementing energy efficiency measures. In Germany, the federal government offers information and advisory services to consumers, in collaboration with DENA, the German Consumer Organisation, and the Federal Office of Economics and Export Control (Verbraucherzentrale, 2010). In Sweden, a network of regional energy offices and local energy advisors has come to play an increasingly important role in informing on insulation measures (Khan, 2006). In the UK, the Energy Saving Trust has been running various energy efficiency campaigns targeted at different audiences (SereNADE, 2007). The roles of the local Energy Efficiency Advice Centers and the Energy Efficiency Partnership for Homes (EEP) have also been enhanced, to create greater interest for improved insulation among users.

¹⁵ Market entrance of new insulation manufacturers has been difficult. Setting up an insulation manufacturing facility is capital-intensive. Fixed costs are significant in the mineral wool industry. Interviews have shown, for instance, that in the case of glass wool production, raw materials account for approximately 38% of the total production cost, energy for 24% and other fixed costs for 24%. Consequently, a high degree of plant utilization is essential to achieve profitability.

4.2.2. Forms of interaction

The main channels of interaction between producers and users have been through: a) sales departments, b) technical support lines, and c) training sessions (both on-site and e-learning). These channels were established and supported by the insulation manufacturers, and government policy interventions have contributed to the development of these forms of interaction since the 1970s. User-producer interaction has become more intense during the past decade.

Manufacturers have offered education (training) and awareness-raising activities to customer groups and to architects (with mixed success in the latter case). Training is offered in a wide range of topics, and energy efficiency is typically addressed in terms of: (a) product choice and application, (b) installation practices, (c) the role of insulation in an energy-efficient building shell, (d) avoidance of thermal bridges, and (e) new regulatory requirements. Distributors, architects and builders claim that it is difficult to keep up-to-date with new products and technical developments, due to a rapid rate of innovation. Two-thirds of building products, for example, have a market-life of less than six years. Therefore, continuous training has become evermore important during the past ten years. The education provided by manufacturers has been complemented by awareness-raising training supported by government bodies. German and Swedish energy agencies, for example, have offered training related to EPCs since the mid 2000s.

Manufacturers of insulation claim to have functional channels of feedback through which they can receive requests and feedback from customer groups, architects and construction firms. These feedback channels, however, are often fragmented and limited to certain areas of expertise: in case of installers, for instance, the feedback received has focused on quality, packaging and installation. Regulatory measures and financial incentives have advanced the role of feedback channels between different customers, user groups and manufacturers by taking a more holistic approach, involving more actors and promoting proximity.

4.2.3. Proximity and mutual interest of actors and networks

Proximity among actors and a mutual interest in interaction have increased following the introduction of the EPBD (2002). The EPBD has become a main driver toward enhanced collaboration among actors by requiring member states to take a holistic approach in developing and applying methodologies, requirements, inspections and certification schemes to rate the energy performance of buildings. National building codes have, as a consequence, tended to shift from a focus on individual building elements and specific areas of expertise to focus on common solutions that improve the overall energy efficiency of buildings. This shift has provided a good incentive for more extensive and continuous collaboration among different building actors. In the UK, for example, the Insulation Strategy Group Home has been established and now provides a platform for active collaboration between insulation manufacturers, installers, trade associations, energy suppliers and government representatives.

Voluntary standards, such as the passive house standard, the standard for zero-carbon buildings, and BREEAM, have also provided new platforms for collaboration between insulation manufacturers and other building professionals, including national research institutes and technical universities. Most mineral wool producers are involved in R&D projects and have developed insulation solutions for low-energy buildings, such as the use of thin insulation layers with high thermal performance. It is notable, however, that this collaboration with actors upstream in the supply chain (designers, developers, construction

companies, etc.) is based mainly on project partnership, and is far less frequent and intense than collaboration with actors downstream with which insulation manufacturers have direct commercial contact.

Another important group (or network) of actors that is based on mutual interest is the group of mineral wool industry associations. Manufacturers of mineral wool insulation have traditionally had strong national and European representation in the form of industry associations. The objectives of these associations include promoting the benefits of better insulation, and maintaining a "dialogue" among producers and with different national, regional and municipal authorities. The Gesamtverband Dämmstoffindustrie (the German Association for Insulation Materials) and the Fachverband Mineralwolleindustrie (the German Association for Mineral Wool Manufacturers) have represented the industry in Germany since the 1970s. Swedisol (the Swedish Mineral Wool Association) is not only a branch organization: it has worked to harmonize methods for testing and measuring various product characteristics since the 1960s. Several bodies exist in the UK, including Eurisol (the Mineral Wool Association), TIMSA (the Thermal Insulation Manufacturers and Suppliers Association) and NIA (the National Insulation Association). These bodies represent manufacturers and other actors (such as suppliers, distributors, and installers) in the supply chain. EURIMA (the European Insulation Manufacturers Association) is the foremost of these organizations, which play a significant role in the development of a legislative framework aimed at improving insulation levels such that insulation measures can achieve their highest energy-saving potential. The growth of a common European approach and policy framework has strengthened the roles of these national industry associations and European policy networks.

4.3. Knowledge development and key learning processes

Processes of learning have been essential for the development of knowledge in the mineral wool insulation industry. The development of internal knowledge has played a crucial role in advancing technology and has been supported by private R&D, extensive patenting activity, and extensive testing activity by insulation manufacturers (Sub-section 4.1). The development of external knowledge has been characterized by training, the raising of awareness, and feedback loops (Sub-section 4.2). The knowledge thus gained has also formed the foundation for the development of institutions and the policy framework (Section 3). Government policies, besides various private investments, have been developed since the 1970s, and have been used to reinforce learning processes, such as learning-by-searching, learning-by-doing, learning-by-using and learning-by-interacting.

Learning-by-searching was supported mainly by private R&D until the 1970s, with contributions from public R&D and building codes from the mid 1970s. Life-cycle consideration and the introduction of environmental standards supported learning-by-searching from the 1990s onwards, by pushing for the development of less resource-intensive insulation products and products with higher performance. In the past decade, voluntary standards further supported learning-by-searching by guiding the direction of search for high-performance products.

Learning-by-doing. Several phenomena have been highly important in the development of the insulation industry, including the availability of private capital, market growth, and the availability of time for learning. Initiatives in development resulted in improved production processes, and a corresponding increase in production capacity, which created the conditions required for essential processes of learning-by-doing and subsequently

Table 3

The influence of policy instruments on relevant factors describing technology development, and actors and networks.

Development	Technology			Actors and networks			
	Direction of search	R&D resources	Mgt of new knowledge	Testing	Sophisticated user group	Form of producer–user interaction	Proximity and mutual interest of actors & networks
R&D		(+)		+			+
EPBD		+					+
Building codes (BCs)							
Early BCs			(+)				
EPBD-induced BCs		+				(+)	+
Standards (e.g. CE label)				+		(+)	
Financial incentives					+	+	+
Information (e.g. advisory centers)					+	+	
Voluntary standards (e.g. passive houses)	+	+	(+)	+	+		+
Testing				+			+
Education & training					+	(+)	+

+ direct influence (+) indirect influence.

advanced know-how. As a result of these initiatives, the productivity (tonnes/production line/year) of one of the largest Swedish manufacturers, for instance, more than doubled in the past ten years. Learning-by-doing has been directly supported by R&D investment and voluntary labels requiring testing, while indirectly supported by public policy instruments designed to promote market growth, such as subsidies, loans and grants. Much of the growth in the renovation market in Germany and the UK during the 2000s has been due to demand generated through the KfW funds and the EEC/CERT programmes.

Learning-by-using is highly hindered by the distance between insulation manufacturers and end-users. Training has been one very important link between insulation manufacturers and other market actors (such as architects, engineers and installers) provides a vital platform for learning. From the mid 2000s, successive revisions of building codes have triggered more intense interaction between insulation manufacturers and user groups. Low-energy (voluntary) building standards have given rise to more clearly expressed demands from users, such as materials with lower thermal conductivity, and thinner insulation for low-energy buildings. Learning-by-using has been directly supported by public policy instruments designed to promote market growth, such as subsidies and loans and has been indirectly supported by public incentives promoting training and certification.

Learning-by-interacting. The EPBD and related policy instruments by promoting cooperation and by raising mutual interest among building professionals (in local, regional, national and European level) concerning strategies of achieving energy efficiency in buildings have been crucial in supporting learning-by-interacting. In addition, voluntary instruments and R&D projects have also provided a good platform for learning-by-interacting.

5. Concluding remarks

The analysis presented here shows that public policy and (public and private) funding have played significant roles in the development of insulation in Germany, in Sweden and in the UK, and it the way in which its use has been adopted. The analysis shows in particular how policy instruments have supported the development of technology and interactions among actors and networks (Table 3). It provides also insight into how

different policy instruments have supported key learning processes.

The development of technology has been based on private and public R&D, accompanied by testing and the establishment of standards. Moreover, early experience of the effect of building codes in Sweden and Germany and later similar experience in the UK show that such codes have been very influential tools in improving levels of insulation. The periodic tightening of energy efficiency requirements has been particularly effective. Building codes induced by the EPBD (2002) and voluntary low-energy building standards, such as the passive house concept, both play a highly significant role in promoting the development of technology (by, for example, setting the direction of search, calling for the allocation of R&D resources, and testing). These codes and standards have also played a major role in pushing high-performance products onto the market. In addition, the EPBD and voluntary standards have undoubtedly forced market actors to find system solutions, and thus to establish various forms of collaboration, based on mutual interest. This has been particularly important in the insulation industry, where platforms for interaction and feedback processes with potential intermediaries (such as architects, construction firms and installers) are limited. In recent years voluntary standards, such as the passive house concept, may have been the strongest drive enhancing technology development.

Financial incentives in Germany and the UK, and enhanced information activities further contributed to better interaction among manufacturers, distributors and users, occasionally establishing the ground for manufacturers to consider demands put forward by users. Financial incentives further provided an essential base for learning and the development of knowledge in the renovation of existing buildings in the 2000s.

In summary, policy incentives have facilitated key processes of learning, which have in turn supported the development of technology and the market. Successively revised building codes have facilitated learning-by-searching, learning-by-using and learning-by-interacting. Voluntary standards have directly influenced learning-by-searching and learning-by-interacting, and indirectly influenced learning-by-using. Financial incentives have directly supported learning-by-using and indirectly facilitated learning-by-doing. The European Energy Performance Directive has given rise to a mutual interest and close collaboration among actors in the insulation market, and has thus given a strong impetus to learning-by-interacting.

Appendix 1

Policy instruments to promote the development and diffusion of insulation materials in Germany

Period	Policy instruments	Comments
1952	Building standard (DIN 4108)	The first minimum requirements for building insulation
1969	Update of DIN 4108	The first specifications of the calculation of the heat transfer coefficient (<i>U</i> -value)
1976	Energy Saving Act (EnEG)	Introducing energy-saving measures in buildings based on component performances
1977	Thermal Insulation Ordinance (WSVO)	Requirement for a maximum value for heat transmission and reference <i>U</i> -values for building components (Fig. 1)
1980s	KfW funds	Energy-efficient rehabilitation and construction funds administered by the German Reconstruction Bank (KfW). Both programmes include thermal insulation measures
1981–1990	2nd Energy Research Programme (R&D)	First time that the National Energy Research Programme calls for "efficient and economically viable use of energy". Fund: EUR 4.1 M (1974–2010)
1984	WSVO	Upgrade of WSVO 1977. The first time requirements set for building refurbishments
1995	WSVO	Upgrade of WSVO 1984. Energy performance measured in kWh/m ² a
1996–2005	4th Energy Research Programme (R&D)	Start-up of Energy Optimized Construction (SolarBau, EnBau) with the focus on innovative technologies and materials, including testing and demonstration in new buildings
1996	KfW funds	Long-term, low interest loans for constructing or purchasing houses with low-energy use
1997	Passive house standard	Voluntary measure established by the Passive House Institute in Darmstad (required <i>U</i> -values of 0.1–0.15 W/m ² K or lower for building insulation materials)
1997	R&D (EnSau)	Introduction of energy-efficient retrofitting research programme in existing buildings.
2000	Information, training and certification	Foundation of DENA, most relevant building projects: Efficient Homes (2003), Efficient Houses (2008), Building Energy Balance Assessment Portal (2009), Database of Experts (2009), Efficient House Quality Mark, REQUEST, quality-assured refurbishment (2010)
2001	KfW funds	Building Restructuring Programme (2001–2005 and 2006)
2001–2003	Future Programme (R&D)	Investing in the Future Programme, including energy efficiency retrofitting of existing buildings, with a budget of EUR 15 M
2002	Energy Saving Ordinance (EnEV)	The first integrated approach (combining WSVO and EnEV) to upgrade <i>U</i> -values of individual building components
2005	KfW funds	Built Ecologically Programme
2005–2011	5th Energy Research Programme (R&D)	Increasing focus on energy efficiency and innovative energy technologies. Merger of different research programmes under Energy-Optimized Buildings (EnOB)
2006–2009	Klimazwei (R&D)	GEKKO, one of the five projects targeting energy efficiency in Klimazwei, with the objective of developing a communication strategy for sustainable construction and refurbishment
2006	Future Building (R&D)	Research on high-tech, energy-efficient building components (for example insulation materials)
2007	Passive house training and certification	Passive house designer training programme and certification (Passive House Institute)
2009	EnEV	Upgrade of EnEV 2002 (<i>U</i> -values of building components in new and existing buildings)
2009	KfW funds	The KfW-Effizienzhaus 55 promotes houses using 55% of the maximum level primary energy use of the required level in EnEV2009; KfW-Effizienzhaus 70 promotes houses using 70% of the maximum allowed level of the required primary energy demand.

Sources: EU Directives 2002/91/EC (EU, 2002), 2010/31/EU (EU, 2010); Energy Saving Acts (EnEG, 1976; EnEV, 2002, 2004, 2007, 2009, 2012); Thermal Insulation Ordinances (WSVO, 1977, 1982, 1995); (BMW, 2010, 2011; dena, 2011; GDI, 2006; IEA, 2011; IPHA, 2010; KfW, 2011; Leão et al., 2008); DIN 4108

Appendix 2

Policy instruments to promote the development and diffusion of insulation materials in Sweden

Period	Policy instruments	Comments
1945	Building code	Including mainly safety and quality standards for insulation materials and training for installers
1956–58	Subsidies and loans	For three-paned windows and additional insulation in family houses
1960	Building Code (BABS 1960)	Requirements on insulation thickness and the performance of the insulation material. Requirements on energy performance classification of mineral wool materials
1967	Building Code (BABS 1967)	Requirements for minimum <i>U</i> -values for individual building components set at a given temperature, and differentiating between walls with heavy (0.4 W/m ² K) and light (0.8 W/m ² K) constructions

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(continued)

Period	Policy instruments	Comments
1975	R&D	Research on energy efficiency (on building material physics and heat transmission, for example)
1975	Building code (SBN 1975)	Requirements for individual building components in specific climatic zones (north and south)
1984	Building Code	Upgrade of the building code: new requirements for walls in two climate zones (0.17 W/m ² K)
1975–1999	Subsidies – tax exemptions	For refurbishment of the existing house stock. The first tax relief was set for a period of two years; it was subsequently extended by no more than 2–3 years at a time.
1988	Building Code (BFS 1988)	Introduction of performance-based building codes; the requirement for an average U-value (U _a) on the whole building envelope was set (see BFS 1988 for the calculation method).
1998	Regional Energy Offices	Local Energy Advisors (LEAs) provide advice and information on energy efficiency
2003–2006	Subsidies – tax exemptions	Improve heat insulation for residential buildings
2006	Building Code (BBR 2006 or BBR12)	Minimum standards on the energy performance (new residential buildings) south 110 kWh/m ² /year, north 130 kWh/m ² /year. Upgraded requirements on the building envelope ($U = 0.5 \text{ W/m}^2\text{K}$).
2007	Specification for the passive house standard	Voluntary scheme – adaptation of the German passive house standard for the Swedish climate
2009	Building Code (BBR16)	Revision of the required level of energy demand in different climatic zones and the extension of the number of zones to three.
2011	Technology procurement	The programme was rapidly canceled due to too few solutions of sufficient quality being presented.
2011	Building Code (BBR19)	Upgrade of the building code: south 90 kWh/m ² /year, middle 110 kWh/m ² /year, north 130 kWh/m ² /year.

Sources: EU Directives (2002/91/EC, 2010/31/EU); Swedish Building Codes (BABS 1945, SBN 1975, BFS 1988, BBR12, BBR16, BBR18); Swedish Ordinance on Financing: SFS 1974:946; SFS 2003:1204; Boverket, 2009, 2010; Energimyndigheten, 2006, 2008, 2009; SOU, 2008.

Appendix 3

Policy instruments to promote the development and diffusion of insulation materials in the UK

Period	Policy instruments	Comments
1978–1990	Home Insulation Scheme	Government grants for energy efficiency investments, including loft insulation
1980s	Building regulations	Requirements addressed in the form of U-values (elemental method)
1992	Information, training and certification	Foundation of Energy Saving Trust, relevant insulation-related programmes: Endorsed Advice Service and Training in more than 50 local information centers (1994), Energy Saving Trust Recommended label (2000).
1990	Building regulation (BR)	Requirement on the thermal performance of insulation materials. Average U-value is set for the whole building envelope
1994	Building regulation	Upgrade of the thermal performance of building components
1994–2002	Energy Efficiency Standards of Performance (EESoP)	Programmes for energy suppliers to provide energy efficiency measures to their customers in the residential sector
1998	Value Added Tax (VAT)	VAT reduction from 17.5% to 5% for energy-saving materials (including all insulation and draught stripping) for vulnerable households, from 2000 for all households
2000	Warm Front Scheme	UK's largest fuel poverty reduction programme providing public grants to vulnerable private households for insulation and heating improvements
2000–2010	Decent Homes Standard	A minimum standard for vulnerable households with regards to heating, weatherproofing and additional facilities, with implementation guidelines (2004, 2006)
2002	Building regulation	Upgrade of the building code. Energy labeling requirement
2002–2008	Energy Efficiency Commitments (EEC1 and EEC2)	Programmes for energy suppliers to provide energy efficiency measures to their customers in the residential sector.
2004	Research Council Energy Programme (RCEP)	Increased focus on energy: in 2011, almost 10% of the total energy budget of RCEP was allocated to energy efficiency activities
2004–2015	Landlords' Energy Saving Allowance	Tax allowance for private landlords to improve the energy efficiency of residential properties, including insulation measures
2006	Building Regulation	Significant upgrade of the code, first time air tightness and thermal bridging are integrated into national legislation
2007	Technology Strategy Board	Business-focused organisation supporting investment in R&D by partnerships via "Innovation Platforms". One of the six platforms is "Low Impact Buildings"
2007	Stamp Duty Relief for Zero-Carbon Homes	Tax incentive for all new homes meeting the zero-carbon standard: no stamp duty on homes costing up to a certain amount and reduced stamp duty in excess of that amount
2008	Code for Sustainable Homes (CSH)	Mandatory rating that goes beyond building regulations. The highest performing level is zero-carbon home
2008	Energy Performance Certificate	As of October 2008, all buildings built, sold or rented in England and Wales must have an Energy Performance Certificate
2008	Carbon Emissions Reduction Target (CERT)	Programmes for energy suppliers to provide energy efficiency measures to their customers in the residential sector
2008	Act on CO ₂ advice line	A 'one-stop shop' information service (EST) to make homes greener, incl. advice on energy-saving, offers from energy companies (insulation) and financial support

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Period	Policy instruments	Comments
2009–2011	Pay As You Save (PAVS)	Pilot project with the involvement of suppliers and end-users addressing energy efficiency retrofitting by subsidizing upfront costs and financing repayments with the savings made. Financing is linked to the property (Department of Energy and Climate Change, EST, Home Energy PAVS)
2009	Community Energy Savings Programme (CESP)	To improve energy efficiency standards and reduce fuel bills in low income areas through community-based partnerships; funded by energy suppliers and electricity generators carrying out energy efficiency measures suited for each property

Sources: Building Regulations (1985, 1990, 1994, 2002, 2006, 2010); Code for Sustainable Homes (CLG) 2006, 2007, 2009, 2010. (BRE, 2009; DECC & EST, 2011; Elswijk and Kaan, 2008; EST, 2011; IEA, 2011; Kilip, 2005)

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Paper III

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Development and diffusion of energy efficient windows

A comparative study of the development paths of energy efficient windows in Germany, Sweden and the United Kingdom

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Abstract

The role of policy instruments to support the introduction and diffusion of energy efficient technologies has been consistently emphasized in the context of resource efficiency and climate change. However, which policy instruments are best suited to promote such technologies is not self-evident. In this study, the development and diffusion of energy efficient windows is analyzed in Germany, Sweden and the UK, along with the policy instruments applied to support this process. The approach is based on the assessment of technology and market development by crossing a literature review and interviews with key actors. The results show that windows' thermal performance has improved between 200-300% and that the market share of energy efficient windows has increased between 15-45% since the 1970s. Important policy incentives for the technology development of energy efficient windows include building codes (with stringent requirements), technology procurement, passive house standards and testing incorporated in these policy instruments. Relevant policy instruments supporting the market development of energy efficient windows include building codes, financial incentives (with minimum requirements), technology procurement and voluntary measures, such as the passive house standard and window labelling.

Key words: Energy efficient window, policy instrument, technology and market development

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1 Introduction

Buildings account for more than one third of total global final energy demand. Of this, almost 70% occurs in residential buildings (IEA, 2010, 2011b; WBCSD, 2009; Ürge-Vorsatz et al., 2012). Roughly one fifth of the total energy-related greenhouse gas emissions worldwide is generated by the residential sector (IEA, 2010; Levine et al., 2007). Scenarios show that the lion's share of future greenhouse gas reduction potential lies in more efficient energy end-use, specifically in reducing the heating (and in warmer climates, cooling) demand in buildings (Levine, et al., 2007; Ürge-Vorsatz, et al., 2012). Technical measures to reduce heating include improvement of building envelope performance, primarily by building insulation (high-efficiency insulation materials and techniques), glazing optimisation and air-tightness maximisation. These improvements can reduce the heating demand by factor of two to four, and up to a factor of eight if other measures are included (Demirbilek, Yalciner, Inanici, Ecevit, & Demirbilek, 2000; Hamada, Nakamura, Ochifuji, Yokoyama, & Nagano, 2003; Hastings, 2004; Levine, et al., 2007; Ries, Jenkins, & Wise, 2009). Windows are of particular interest as they represent a significant part of heat leakage across the building envelope and thus are an essential technology to achieve energy savings and greenhouse gas mitigation. Depending on the climatic zone, region and building type, heat losses through windows can vary between 4 and 27% of the total heat loss of the building (Nemry et al., 2008). Building studies show that replacement of old windows and doors together with other air-tightness repairs, using off-the-shelf technologies, can reduce the heating demand by 35% on average, and according to a study in the UK, by an additional 30-40% when combined with other energy efficient technologies (Bell & Lowe, 2000). The energy saving potential could be accelerated by increasing the currently low annual renovation rate in Europe, which is between 0.5-2.5%, to an average of 3% (BPIE, 2011).

This paper presents a comparative study of the development path of energy efficient windows in Germany, Sweden and the UK. These three countries are of interest due to their important role in window technology development and market development. The technology development is described in terms of the thermal performance of windows in the broader context of the history of glazing and window structures. Germany and the UK are of interest in this case, due to innovations in the plastic window frame and glass industries, which contributed greatly to the introduction of energy efficient windows. Market development is described in terms of the diffusion rates of energy efficient windows in the broader context of the structure of the market supply. Germany and Sweden are of interest here, due to similarly high diffusion rates, but different market structures. Germany and the UK can be compared based on different diffusion rates under similar market structures. In addition, these countries are targeted due to the diverse character of policy initiatives applied to support the introduction and the diffusion of energy efficient windows. This paper discusses how different policy instruments supported technology and market development. Its goal is to provide insights into how various policy instruments have, or have not, supported trajectories of energy efficient end-use technologies in buildings.

This research is based on literature review and interviews. In total, forty interviews were conducted with product developers, marketing and sales professionals and other representatives of window manufacturing companies, European and national industry associations, research institutes and authorities as well as other experts in the field. The interviews were used to understand the development of the definition of energy efficient windows in the three countries over time (see Figures 2, 4 and 6), and to obtain data and experts' views on the technology and market development of windows. A literature review of market research, company reports, policy briefs and academic journals was used to complement and to triangulate data obtained from interviews and market structure data as well as to gain a better understanding of the perception of the role of policy intervention in different countries.

The outline of the paper is as follows: Section 2 provides a brief description of the conceptual framework and the definition of energy efficient windows applied in the study, Section 3 presents a brief history of the development of window components, such as glazing and window structures; Sections 4, 5 and 6 provide an insight into the window market structure, the policy landscape and the role of these in the technology development and market development of energy efficient windows in each respective country. In Section 7, the role of policy instruments in the technology and market development of energy efficient windows under different countries' market structures is discussed and compared. In the concluding remarks, general policy implications for technology development and market development are discussed.

2 Conceptual Framework

The focus of this study is on the introduction and diffusion of energy efficient windows and the role of different policy instruments and market structures in their technology and market development. Energy efficiency of windows is mainly determined by their thermal performance, i.e. heat loss through the windows' surface, which is measured in U-values². As the thermal performance of windows has improved over time, the definition of energy efficient windows has also changed. The definition of energy efficient windows at different times is based on literature review triangulated by interviews with market actors, and presented in Figures 2 (Sweden), 4 (Germany) and 6 (UK) for the three different countries. In this paper, technology development is described in terms of the *thermal performance of windows* (U-value) in the context of the historical development of window components, such as window panes (glazing) and window structures (frames, sashes, gas filling and fittings). The market development is described in terms of diffusion rates and price. Diffusion rates show *energy efficient window sales* (and/or market share) in relation to the annual or total window sales. The

² U-value (W/m²K) measures the heat flux (Watt) through the window surface (m²) at 1K or 1°C temperature difference between inside and outside.

diffusion of energy efficient windows is influenced by the market structure and different policy instruments. *Market structures* are described by parameters³, such as 1) *market concentration*, e.g. *number of companies, size of companies and their market share*, 2) *technology capability*, e.g. *R&D and experience* (Garud, 1997; Nelson & Winter, 1977a, 1977b, 1982), 3) *product differentiation*, and 4) *actors' relations*, e.g. *networking* (Håkansson, 1987; Kamp, Smits, & Andriessse, 2004; Lundvall, 1988). Technology development and market development of energy (efficient) technologies in a policy context has been accentuated and increasingly applied before (see e.g. (Diaz-Rainey & Ashton, 2009; Kemp, 1997; Stoneman & Diederer, 1994), also called as market transformation programmes aiming at changing the market structure (Geller & Nadel, 1994; Neij, 2001). Policy instruments considered in this study include those focusing on energy efficiency in buildings in general. The focus of the policy discussion is on how specific policy instruments have influenced the development and diffusion of energy efficient windows. These policy instruments fall into one of the following categories: a) regulatory instruments (e.g. building codes), b) fiscal instruments (e.g. grants, subsidies, loans, tax exemptions), c) economic and market based instruments (e.g. technology procurement), d) information programmes (e.g. labelling, advice centres) and e) voluntary measures (e.g. the passive house standard, codes for sustainable buildings).

3 The emergence of energy-efficient windows – a brief historical overview

The technology development of energy efficient windows has, in some aspects, been similar in Germany, Sweden and the UK. The developments of the past 30 years can be characterized by continuous incremental changes in *window panes* (glazing, coatings and solar control glasses) and *window structures* (frames, sashes, spacers, inert infill gases and mounting). There have been two important innovations in the glazing industry in recent decades: i) the development of the float glass process⁴ in the 1960s and ii) the introduction of low-emissivity (low-e) coatings in the 1970s. With the application of low-e coating, together with multiple glazing and gases between the window panes, heat transmittance has been reduced from 6.0 W/m²K for single glazing to 0.4 W/m²K for a triple insulating glass unit.

3.1 Energy efficient glazing

The development of energy efficient glazing has a common past in many countries. The float glass process was introduced in 1959 by a relatively small family business, Pilkington (UK) and shortly thereafter the technology was commercialized by providing

³ Parameters, such as production capacity (e.g. access to capital)(Freeman, 1988), suppliers, competition (e.g. exit and entry barriers), free information flow (Carlsson & Jacobsson, 1997) and spill-over are also present in the study to a limited extent.

⁴ The float glass manufacturing process involves “discharging the ribbon of molten glass from the furnace, floating it onto a bath of molten tin and cutting it directly without polishing” (Barker, 1994; Teece, 2000).

geographic technology licensing rights to existing glass manufacturers. In the 1970s, Pilkington became a public company and it made two major acquisitions; one of them was FlachGlas (Germany). In 1975, FlachGlas, with a license from Glaverbel (France), marketed the first high heat insulating glass with a low-e coating (Gläser, 2008). This product was a milestone in the technology development of glazing for buildings and it set the direction for other manufacturers when building codes with specific energy requirements came into force in the 1970s. The next big step in low-e technology development was in the production process in 1980⁵. Due to colour-deficiencies, however, gold-coating was changed to silver-coating, which remained standard in Europe until 1993 (Gläser, 2008). Since the 2000s, silver-based coating has been produced in in-line magnetron coating plants. This technology offers high production capacity and serves as the standard production method for high heat insulating glass units worldwide.

3.2 Energy efficient structures

The development paths of window structures, frames and sashes varied among countries, depending on the resources available and traditions around window- frame materials and their manufacturing. While the Swedish window market was characterised by wooden-framed windows, the German and the UK market was more diverse, with around 50% market dominance of UPVC-framed (unplasticised polyvinyl chloride or hard polyvinylchloride) windows. In the 1990s, the introduction of IGUs, the application of different gases and spacers in between the panes, has contributed to the further development of window thermal performance.

The development path of UPVC-frames follows that of plastic manufacturing and PVC production in Germany. BASF started manufacturing PVC in the early 1930s and Dynamit Nobel produced the first PVC window system in 1955. In the 1960s, UPVC-framed windows spread first throughout Germany and then from the late 1970s also to other European countries⁶. The Hanover Trade Fair (1975) played an essential role in the dissemination of UPVC-framed windows and also motivated British manufacturers to look into potential replacements of wood and aluminium windows. Not long after the fair, one of today's largest UPVC window manufacturing companies in the UK, Epwin, was established. However, due to technical complexities and investments involved in extruding UPVC, German materials and know-how were needed for the operation (Van de Vliet, 1994). The cooperation between window manufacturers and plastic component manufacturers, with expertise in plastic extrusion, led to the installation of the first

⁵ In 1980, the first batch-type conventional sputtering plant for coating large size float glasses was built and set into operation by Interpane in Germany (Gläser, 2008). The advantage of these gold-coated glasses was that they could be shipped and processed into insulating glass units more easily.

⁶ This study focuses on Europe, the market development of UPVC windows had a slightly different pathway in North America (Cook, 1971; Gläser, 2008; Pederson, 1997).

“made in UK” double glazed UPVC-framed windows in 1979. Since then, changes have been made mainly to the thickness of the frames. The life expectancy of these window frames are around 30 years (Clift, 2006).

While UPVC window manufacturing has experienced dramatic development over the past 25 years, only marginal changes took place in wooden window structures. Following the application of additional window panes, from single to double glazing, to insulating glass units (IGUs) and to triple glazing (in Sweden), the frame structures needed to be changed. As a result, the U-value improved from about 6.0 to 2.0 W/m²K. Based on the principle that the deeper in the frame the panes are set, the better U-value can be achieved, there has been some advancement based on the depths of the sashes in the past ten years. These include the means of sealing and insulating frames by combining alternative, highly insulating materials with wooden frames in order to break thermal bridges.

The introduction of Argon-, Krypton- and Xenon-filled IGUs contributed to the improvement of the thermal performance of glazing and meant that, depending on the gap distance between window panes, U-values could be improved by 0.5-1.0 W/m²K (Bülow-Hübe, 2001). U-values have further improved recently with the application of warm-edge technologies, i.e. spacers in between the window panes. Although the improvement is marginal (0.1-0.2 W/m²K), there are still some co-benefits with their application. First, with the use of spacers, the risk of condensation can be reduced. Second, as the glazing U-values decrease below 1.0 W/m²K, marginal changes in the frame structure, mounting and warm-edge technologies become significant for the overall performance.

4 The development path of energy efficient windows in Germany

4.1 Window market structure

The market structure of the German window manufacturers has been fragmented and can be characterized by plentiful small, often family-owned, enterprises. In 2010, the aggregated market share of the top ten window producers accounted for only 22% of the market (Interconnection, 2010a). Investments in technologies like extruders have led to high debts and bankruptcies in smaller companies⁷. Moreover, the downturn of the construction sector in the mid 1990s led to acquisitions and mergers among window manufacturers. These mergers resulted in more capital for production capacity investments, and in more innovations, via technology and knowledge spill over. In all, the technology capability of the window manufactures relies on five decades of experience, specifically in plastics engineering (UPVC frames) and performance

⁷ In 2010, the market consisted of more than 8 500 companies, out of which 90% had annual sales < 5M Euros. The rate of insolvency in the sector has been twice as high as the average industry insolvency rate (Horst, 2005).

testing⁸. Interviews indicate that private R&D investments have been rare, especially in the smaller companies.

In terms of window components, UPVC is the dominant window framing material, with a continuously growing market share since the mid 1970s. After the development of UPVC frames in the 1970s, several German UPVC extrusion system companies established window component manufacturing facilities abroad. Partly through them, and partly through other platforms (e.g. testing, fairs, acquisitions, export), Germany became an important actor in the international window market - as a transferor of know-how, components and ready-made products.

Due to the number of window manufacturers, pressed prices and the high solvency rate, product differentiation has been a significant challenge in the German window market. In recent years, actors' strategies to address this problem and increase the product range included offering consulting services with product sales. Fierce competition and the fear of know-how loss greatly hinders strategic actions toward networking, partnerships and experience sharing (Horst, 2005).

4.2 Policy instruments for energy efficient windows

Germany has a long history of various policy incentives for addressing energy efficiency in buildings. Different energy saving regulations have driven a clear trend toward reduced energy consumption in buildings since 1976. As a consequence of the implementation of the Thermal Ordinance adopted in 1977, the energy demand for heating has decreased by about 30% (H. Geller, et. al., 2006; VFF, 2010). Even though each upgrade of the Ordinance required approximately 30% better overall energy performance, as the requirements could be met by improvements of the heating system, it seemingly did not support the performance improvement of individual building components, such as windows. The introduction and allocation of financial incentives from the 1990s, mostly in the form of different KfW funds (see Appendix 1) aimed at supporting energy efficient upgrading of new and existing buildings. At the same time, voluntary measures, such as the German passive house standard, also gave signals to the industry to produce windows with much better energy efficiency standards than were legally required. (Appendix 1 provides an overview of the most relevant policy instruments for the development and diffusion of energy efficient windows.)

4.3 Development and diffusion of energy efficient windows

The introduction and diffusion of energy efficient windows was slow due to a relatively fragmented market and low R&D investments of smaller companies. Early development in the 1970s-80s was supported through innovations in glazing and the plastic industry

⁸ Window performance testing has been taking place at the national testing institute: Institut für Fenstertechnik, in Rosenheim.

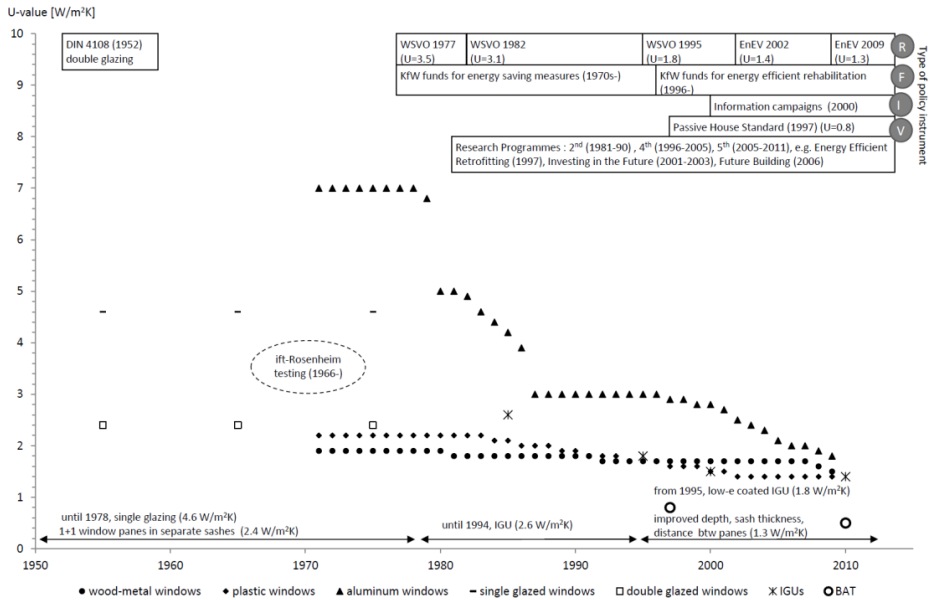
and testing of window performance. As a result, insulating glass units (IGU)⁹ came to replace the poorly performing uncoated single or double paned windows, which had dominated the residential window market until the 1970s. These IGUs had a U-value of around 2.6 W/m²K and remained the principal window type until the mid 1990s (VFF, 2010). The 1990s process innovation in the coating industry made the diffusion of low-emissivity coated IGUs possible. These windows, with low-emissivity coating and advanced insulation and sealing technology of the frames, had up to three times better insulation values than windows with single glazing. Technology development of the late 1990s also included improvements in the window structure in terms of the depth and thickness of sashes, as well as the distance between panes. The average U-value of windows produced between 1995 and 2002 was around 1.8 W/m²K (VFF, 2010), which was also a conditional performance requirement for replacement windows in the Thermal Ordinance of 1995. The Thermal Ordinances of 2002, 2007 and 2009 set new and gradually more stringent requirements resulting in a gradual technology development over time. Typical U-values of windows sold in the period of 2003-2005 were 1.5 W/m²K and 1.4 W/m²K from 2006 onward (VFF, 2010). From the mid 1990s, different KfW funds accelerated the market uptake of these energy efficient windows. The market development was also supported by continuous testing and certification guaranteeing the performance of the windows. From the beginning of the 2000s, the emerging application of passive houses required windows with U-values of 0.8 W/m²K. This not only improved the energy performance of the windows, but also facilitated product differentiation by creating a market for UPVC windows with high thermal performance.

In all, the market share of energy efficient windows has increased over time and in 2010 the market share of windows with a U-value of 1.3 W/m²K (or lower) was around 45%¹⁰ (VFF, 2010). The considerable quality improvements since the 1970s, the market incentives provided by the government and relatively low prices made UPVC windows an attractive product on the market. The price of UPVC windows, which on average cost 35% less than wooden windows, was relatively stable in 1990s and was reduced in the mid 2000s (Horst, 2005). The general view of market actors is that this fairly stable price over time is due to the industries' inability to transfer the constantly growing raw material¹¹ prices to end-users (Interconnection, 2010a). In addition, the high demand and excess capacity also put pressure on many small enterprises to provide windows at reduced prices.

⁹ Insulated glass units (North America and Australia) or insulated glazing or glass (Europe) are multiple glass panes assembled into units; framed in a sash or frame.

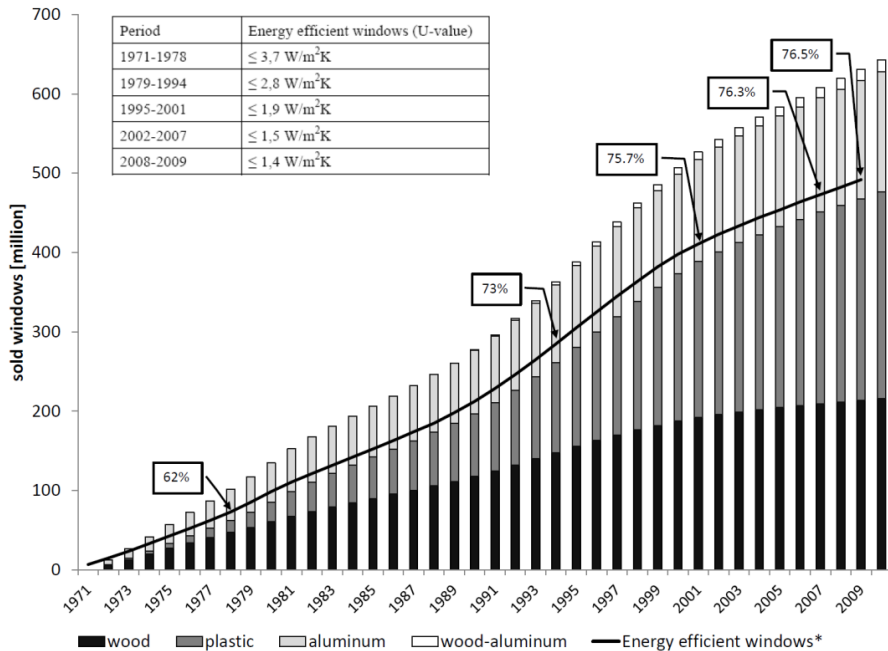
¹⁰ In 2010, windows with a U-value of 1.8 W/m²K or lower were more widespread, with about 77% of the market share (VFF, 2010).

¹¹ The cost of both window panes and UPVC frames are highly dependent on oil prices, both as raw material and as energy source for production.



U-values represent the average U-values sold in respective years in Germany (Source modified from VFF, 2010, complemented with interviews)

FIGURE 1 POLICY INSTRUMENTS FOR THE DEVELOPMENT OF ENERGY EFFICIENT WINDOWS IN GERMANY (1950-2010)



** The rate of energy efficient windows sales in relation to the total annual window sales. (Source modified from VFF, 2010 and interviews with market actors).*

FIGURE 2 MARKET SHARE OF ENERGY EFFICIENT WINDOWS IN RELATION TO TOTAL WINDOW SALES IN GERMANY

5 The development path of energy efficient windows in Sweden

5.1 Window market structure

The Swedish window market has been very concentrated, both in terms of aggregated market share and type of window frame material. Due to Scandinavian natural conditions and an advanced joinery tradition, more than 90% of the Swedish windows have wood or wood-metal frames (Kiss & Neij, 2011). In the 2000s, two window manufacturers with an estimated aggregated market share of 70% dominated the internal market. The top window companies dictate trends, price levels and make the market entrance for new firms very difficult. The technical capability relies on the knowledge and long experience in joinery products and the high level of private R&D. In 2008 approximately 1% of the larger window manufacturers' turnover was earmarked for energy efficiency advancements, modelling and testing activities (Kiss & Neij, 2011). The production process specialisation of 1990s led to higher production rates; recently, however, low demand has resulted in low capacity utilisation levels. In 2009, less than 52% of the built capacity was used (Interconnection, 2010b). The degree of information flow has been gradually increasing mainly through channels of acquisitions and mergers as well as networking supported by various policy instruments (see section 5.2).

5.2 Policy instruments for energy efficient windows

Policy intervention supporting energy efficient windows in Sweden has been characterized by a mix of different measures over time (see Appendix 2). The periodically updated building codes, with specific requirements for building components, paved the way for the development of more efficient windows up to the 1980s. The first building code (SBN75) setting energy performance requirements for windows entered into force in 1977. In the 1980s, the focus was on improving window quality and performance, in part through the introduction of a labelling system (P-label). In the mid-1990s, technology procurement programs¹² were introduced to bring better-performing windows to the market. In addition, information activities were developed for promoting energy efficient windows. Free advisory services on energy efficiency issues have been in place since 1997 and energy labelling for windows since the mid 2000s. Although short-term subsidies and tax exemptions have characterized the policy arena since the 1970s, specific energy performance requirements for windows were introduced only in 2004.

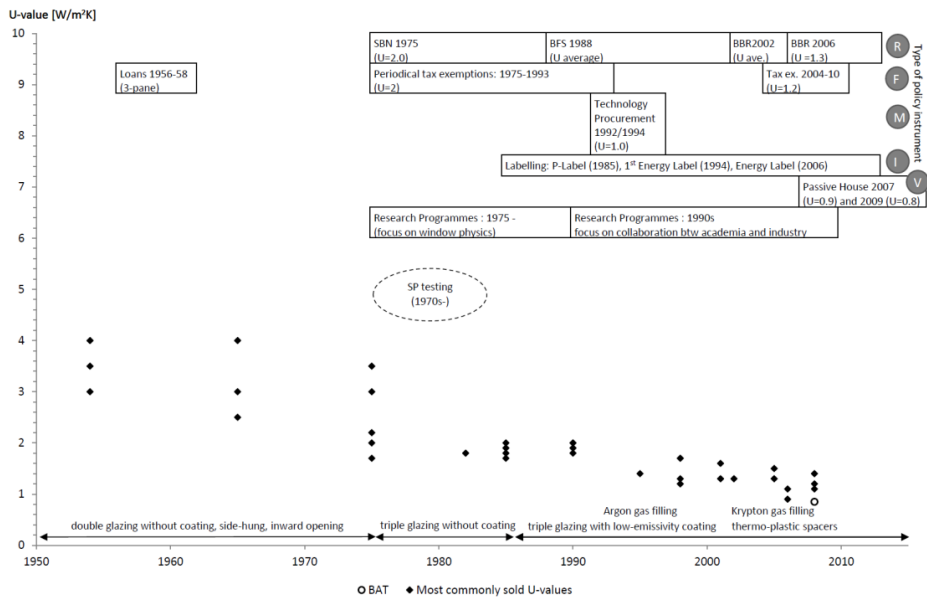
¹² Technology procurement aims at stimulating and accelerating market introduction of new technologies by engaging different market actors on one hand to develop new and required products and on the other hand to ensure a purchase-group for the newly developed technology. The procurement for windows also included testing and labelling.

5.3 Development and diffusion of energy efficient windows

The results of the literature review and the interviews in Sweden show that policy instruments and the structure of the window market have had an important influence on the technology and market development of energy efficient windows. The technology development was supported by both private and public R&D, testing and stringent building codes with component specific requirements in the 1970s. In addition, intensive collaboration between industry and academia also contributed to the increasing technical capability of the industry. Both technology and market development of energy efficient windows was supported by a strong Swedish window industry investing in R&D and knowledge development through networking.

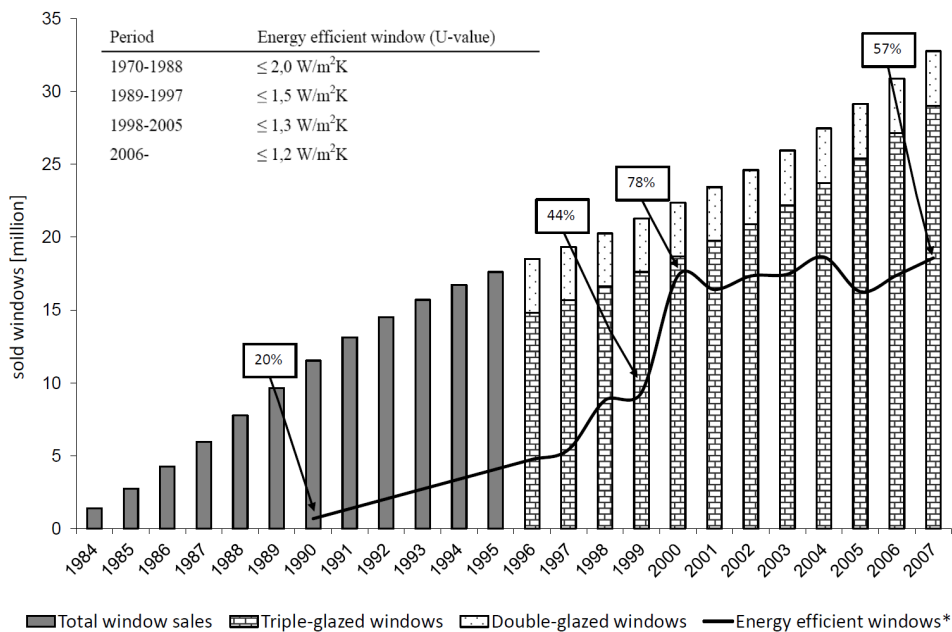
In the mid 1990s, technology procurement programs enhanced this development by introducing windows with a U-value of 1.0 W/m²K. SP, the Technical Research Institute of Sweden, played a significant role in meeting the requirements of the procurement. In addition, the technology procurement programme provided a sound networking platform for market actors, such as building companies, window manufacturers, glass manufacturers, SP and national bodies. In the 2000s, technology development was further triggered by various voluntary measures, such as the energy labelling for windows and the German passive house standard adapted for Sweden in 2007¹³. The concentrated market structure facilitated the fast emergence of energy efficient windows in the Swedish market. When larger manufacturers introduced windows with U-values of 1.3 W/m²K in 1998 and of 1.2 W/m²K in 2008, sales figures of energy efficient windows showed a sudden increase (see Figure 4). In 2007, an estimated 70-80% of the total window sales had U-values of 1.3 W/m²K or below, while the market share of windows with U-values of 1.2 W/m²K or lower was about 50%. In addition to the above shown actors' strategies, subsidies with thermal performance requirements (2004-2010) had also a slight influence on the market development of energy efficient windows; the subsidy led to more than 200 000 m² of improved window surface (>150 000 windows) by 2009 (Boverket, 2009). With the advancement of glazing technologies, the price difference between an energy-efficient window and a non-energy efficient window decreased to an estimated 5-7% by 2008.

¹³ The U-value requirement of the latter was 0.8 W/m²K in 2007, which is close to the best available technologies (0.7-0.6 W/m²K).



U-values represent the most common U-values produced in respective years in Sweden (Source modified from Kiss & Neij, 2011)

FIGURE 3 POLICY INSTRUMENTS FOR ENERGY EFFICIENT WINDOWS IN SWEDEN (1950-2010)



** The rate of energy efficient windows sales in relation to the total annual window sales. (Source modified from Kiss & Neij, 2011)*

FIGURE 4 MARKET SHARE OF ENERGY EFFICIENT WINDOWS IN RELATION TO TOTAL WINDOW SALES IN SWEDEN

6 The development path of energy efficient windows in the UK

6.1 Window market structure

The window market structure in the UK is vertically integrated, characterized by UPVC- and aluminium-frame manufacturers as well as joineries supplying window panes to companies of many sizes assembling windows from prefabricated elements. In 2009, the aggregated market share of the top eight window manufacturers was 22.4% (Interconnection, 2010c). The windows, manufactured and assembled in the UK, were initially made from wood but since the 1980s, as an alternative material for wood and metal frames, UPVC frames have been used increasingly in the residential sector. Initially, while German materials were used in the 1980s, UK window manufacturers had invested in extruders to manufacture UPVC frames and gradually built experience in plastic manufacturing (Van de Vliet, 1994). The short experience in plastic manufacturing and the lack of private R&D and testing activities, however, suggest a low technology capability. The integrated production process, on the other hand, resulted in high production capacities and better margins. By the end of 2000s, UPVC accounted for more than 80% of the residential market (Palmer, 2009).

6.2 Policy instruments for energy efficient windows

The UK has a relatively young history of policy interventions for energy efficient buildings and building components. Energy efficiency received increasing focus from the mid 2000s and policy packages of regulative, financial and informative measures have been applied (see Appendix 3). Financial incentives have a longer past in the UK. Government grants for energy efficiency upgrades were introduced in the 1970s, however, window replacement was not included in these schemes until the late 1980s and these grants were typically lacking stringent thermal requirements. Energy-efficiency commitment schemes (EST, EEC1, EEC2, CERT), with the involvement of energy suppliers, were introduced in the mid 1990s and since then have been continuously supporting energy efficiency measures, including the diffusion of double-glazed windows (Shorrock & Utley, 2003). Later, in the mid 2000s, innovative financial schemes, such as the Landlord Saving Allowance and the Pay as You Save scheme, recognized the urgent need for solutions to finance upfront investment costs. In the UK, building codes with specifications for windows were introduced only in 1990 and even then with low levels thermal performance requirements. First, the Decent Home Standard (2000) and the building code (2002) upgraded based on the European Building Performance Directive (2010/31/EU) set relatively stricter requirements for window performance. In addition, the voluntary labelling system for windows¹⁴, since 1999, has

¹⁴ The number of BFRC labelled windows is continuously growing: from 115 windows in 1999 increased to 450 in 2008. In 2008, 90 companies participated in the scheme.

played a relevant role and has been gradually integrated into building codes and energy suppliers' obligation schemes.

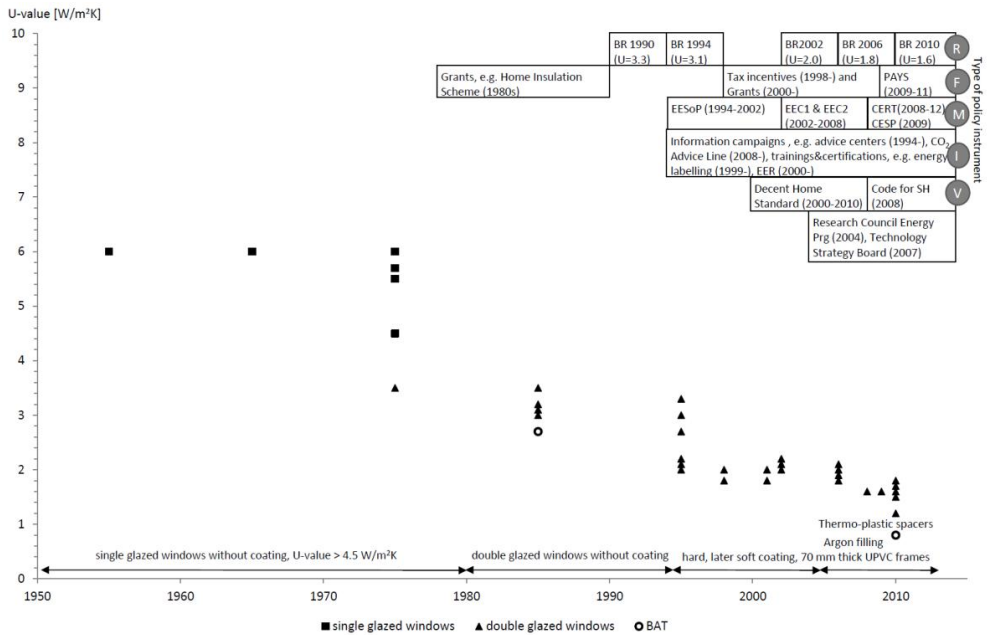
6.3 Development and diffusion of energy efficient windows

The early technology and market development of energy efficient windows was slow in the UK, and it was only to a limited extent supported by window manufacturers and the government. The results of this study indicate that no significant changes took place in terms of the development of thermal performance of the UK window stock until the mid 1990s. Policy support for technology development came fairly late (see Figure 4). The building code of 1990 only required double glazed windows with U-values of $\leq 3.3 \text{ W/m}^2\text{K}$ ¹⁵ and it was not until 2002 that a more stringent code was introduced with U-values requirements of $\leq 2.0 \text{ W/m}^2\text{K}$. The tightening of the building code, however, had an effect on the market: smaller companies, with low volumes, not being able to comply with the requirements had to shut down their activities. Early financial incentives for energy efficiency did not support energy efficient windows.

In 2002, energy-efficiency commitment schemes (EEC) combined with information activities (e.g. EST, CO₂ advice line, energy labels) supported the introduction of double glazed windows. The ownership of double glazed windows increased from 7.8% (1974) to 74.9% (2001) (Shorrocks & Utley, 2003)¹⁶. However, these windows had in general a lower thermal performance than the requirements of the building code for new buildings ($1.6 \text{ W/m}^2\text{K}$). In 2010, 80% of windows produced in the UK only met the minimum requirement; the remaining 20% performed mostly in the range of 1.3-1.4 $\text{W/m}^2\text{K}$. In all, the market share of energy efficient windows has increased and in 2010, the sales of energy efficient windows were about 15% of total window sales. The price of double glazed windows was static over time. According to interviews with window manufacturers, UPVC windows have become more than 50% cheaper with better performance. This is partly due to technology learning and partly to fierce competition in a mature (close to declining) market with over capacity and market saturation. Since more than 80% of UK properties have some form of double glazing, UPVC market sales reached a peak by the mid 2000s. The production of triple glazed windows has only started recently and today the price is approximately 30% more than the double glazed unit prices.

¹⁵ Typically, the U-values of single glazed windows in place were in the range of 4.5-5.6 $\text{W/m}^2\text{K}$.

¹⁶ Despite double glazing being pricier than cavity wall insulation, the uptake of double glazed windows was twice as much as cavity insulation (Shorrocks & Utley, 2003). Interviews indicate that, in addition to co-benefits, such as noise protection, the "natural" replacement of single glazed windows was an easier action than insulation.



U-values represent the typically sold U-values in respective years in the UK (based on interviews with window manufacturers and other professionals related to the window industry)

FIGURE 5 POLICY INSTRUMENTS FOR ENERGY EFFICIENT WINDOWS IN THE UK (1950-2010)

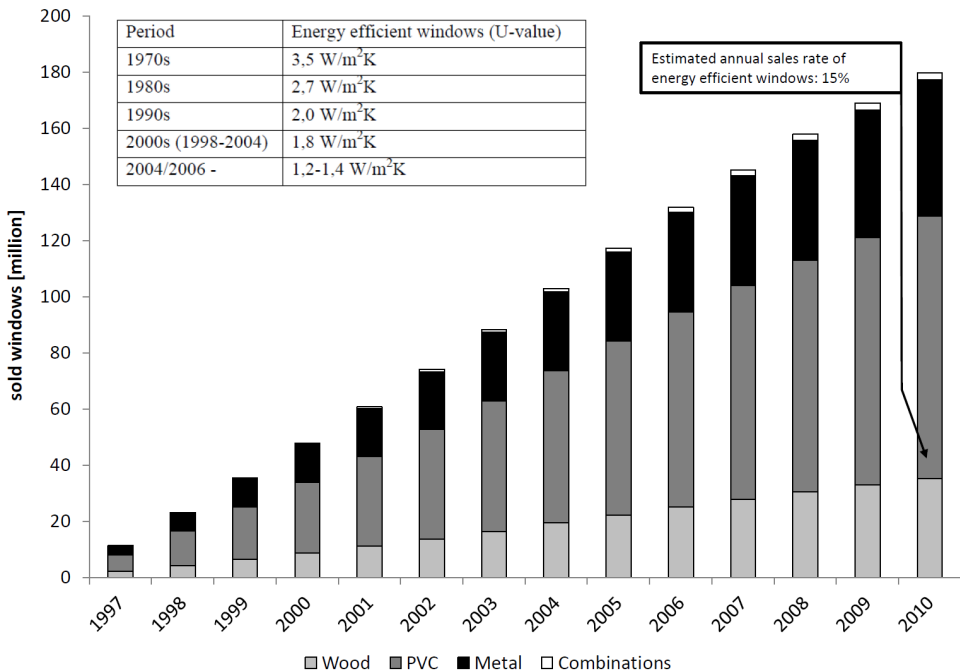


FIGURE 6 MARKET SHARE OF ENERGY EFFICIENT WINDOWS IN RELATION TO TOTAL WINDOW SALES IN THE UK (SOURCE: INTERCONNECTION, 2010C; AND INTERVIEWS WITH MARKET ACTORS)

7 The role of policy instruments in the introduction and diffusion of energy efficient windows

In general, the introduction and diffusion of energy efficient windows was slow, partly due to the fragmented market structure in Germany and the UK and partly due to the lack of governmental incentives. Early technology development was sustained by the testing activities of larger window manufacturers in Germany and Sweden, which in turn contributed to better technology capability and know-how of window manufacturers. In addition, by being an essential component of other policy programmes of the 1990s, such as technology procurement and labelling, testing contributed to increased feedback, knowledge development and networking in the window industry.

Building codes played a very important role in the introduction of energy efficient windows. In Sweden, building codes were introduced in 1970 guaranteeing U-values of $2.0 \text{ W/m}^2\text{K}$. In Germany, building codes were introduced at the same time, but lacked stringent requirements on building components, and thus didn't support early technology development. It was not until the mid 1990s that building codes affected the introduction of energy efficient windows, by requiring a U-value of $1.8 \text{ W/m}^2\text{K}$. In the UK, building codes were introduced in 1990, but these only required double glazed windows with U-values of $\leq 3.3 \text{ W/m}^2\text{K}$. Both in Germany and the UK, the EBPD-induced building codes in 2002 were the first building codes to promote the application of better performing windows with U-values in the range of $1.3\text{-}1.4 \text{ W/m}^2\text{K}$. In addition to the building codes, technology procurement and the passive house standard played an important role in promoting energy efficient windows. In Sweden, the technology procurement required windows with U-values of $1.0 \text{ W/m}^2\text{K}$, which were available already in the mid 1990s. In Germany, the early introduction of the passive house standard played a significant role in technology development of energy efficient windows and product differentiation; in 1991 the standard required a U-value of $0.8 \text{ W/m}^2\text{K}$.

Technology development through R&D, testing activities and building codes paved the way for market diffusion of energy efficient windows. Diffusion was further enhanced by financial incentives (Germany, Sweden, UK), energy suppliers' obligations (UK), advanced voluntary building standards (Germany, UK) and labelling (Sweden, UK). The major difference in the introduction and diffusion of energy efficient windows was due to the difference in building codes. The stringency of the building codes was important in the diffusion of energy efficient windows in Germany and Sweden. In the UK, the absence of stringent regulations resulted in the diffusion of windows with poor thermal performance. This study also shows that financial incentives have an effect on technology diffusion; however, it indicates the importance of having stringent minimum requirements attached to such incentives. In Germany, the early and timely introduction and allocation of financial incentives for energy efficient upgrades, by requiring certain

performance levels, facilitated the uptake of windows with improved performance at only a slightly higher consumer price. Subsidies with energy performance requirements also contributed to the diffusion of windows with better U-values in Sweden. In the UK, financial incentives did not include stringent energy performance requirements and were thus insufficient to realise considerable energy saving. Window labelling schemes, in Sweden and the UK, seem to have created new markets for energy efficient windows and also contributed to product differentiation. Networking among market actors seems to have been an important condition for the diffusion of energy efficient windows. Swedish labelling activities, for instance, created a new platform for window manufacturers for knowledge development and networking, consequently contributing to the further development of energy efficient windows (Kiss & Neij, 2011). Apart from labelling, networking has also been supported by technology procurement, EPBD-induced building codes and advanced building standards.

8 Concluding remarks

This study has shown that the stringency and timeliness of building codes are crucial to the diffusion of high performing windows; in the absence of stringent regulations, poor window technologies can lock in the market for the following 20-30 years. The implementation of the EPBD-induced building codes, extended to renovations, can tap the huge energy saving potential in the existing building stock. This study also concludes that testing, as an important tool of continuous feedback for manufacturers and an essential component of other policy programmes, has contributed greatly to the introduction of energy efficient windows. Financial incentives can also facilitate the market diffusion of energy efficient windows; it is however, very important to have stringent minimum requirements attached to them. Labelling, in addition to energy performance information, has helped establish a common networking and knowledge sharing platform for window manufacturers.

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TABLE 1 POLICY INSTRUMENTS TO PROMOTE THE DEVELOPMENT AND DIFFUSION OF ENERGY EFFICIENT WINDOWS IN GERMANY (1950-2010)

Modified source from (Kiss, Gonzalez, & Neij, 2012); Other sources: EU Directives 2002/91/EC (EU, 2002), 2010/31/EU (EU, 2010); Energy Saving Acts (EnEG, 1976; EnEV, 2002, 2004, 2007, 2009, 2012); Thermal Insulation Ordinances (WSVO, 1977, 1982, 1995); (BMWi, 2010, 2011; dena, 2011; GDI, 2006; IEA, 2011a; IPHA, 2010; KfW, 2011; Leão, Müsch, Fisch, Leão, & Kuchen, 2008; Schröder, Ekens, Power, Zulauf, & Lowe, 2011)

Period	Policy instruments	Description / requirements
1952	Building Standard (DIN 4108)	The first minimum requirements on insulation, including recommendation for double glazing.
1966	Testing	Foundation of ift-Rosenheim testing institute for window, facade and door standards, research, accreditation, proof of tests or calculations and certificates.
1976	Energy Saving Act (EnEG)	The first call for energy saving measures in buildings; airtightness of windows and quality glazing are mentioned.
1977	Thermal Insulation Ordinance (WSVO)	Requirement for a maximum value for heat transmission as average U-value of the building envelope with reference U-values of building components in new buildings ($U_w=3.5 \text{ W/m}^2\text{K}$).
1970s	KfW funds	First time that energy saving programmes are on the agenda of the German Reconstruction Bank (KfW).
1981-1990	2 nd Energy Research Programme (R&D)	First time that the National Energy Research Programme calls for “efficient and economically viable use of energy”.
1982 / 1984	WSVO	Upgrade of WSVO 1977 and conditional requirement are set for windows in the existing building stock ($U_w=3.1 \text{ W/m}^2\text{K}$).
1990	KfW funds	Housing Modernisation Programme addressing the East German housing stock.
1995	WSVO	Upgrade of WSVO 1984; energy performance is measured in kWh/m ² a; conditional requirement for windows in the existing building stock ($U_w=1.8 \text{ W/m}^2\text{K}$).
1996-2005	4 th Energy Research Programme (R&D)	Energy Optimized Construction (SolarBau, EnBau) with the focus on innovative technologies and materials as well as testing and demonstration in new buildings.
1996	KfW funds	CO ₂ Reduction Programme: long-term, low interest loans for constructing or purchasing energy saving houses. Replacement windows are promoted under this scheme.
1997	Passive house standard	Voluntary measure established by the Passive House Institute in Darmstadt (required U-values of $0.8 \text{ W/m}^2\text{K}$ or lower for windows.)
1997	R&D (EnSau)	Introduction of energy efficient retrofitting research programme in existing buildings.
2000	Information, trainings and certification	Foundation of DENA, most relevant building projects: Efficient Homes (2003), Efficient Houses (2008), Building Energy Balance Assessment Portal (2009), Database of Experts (2009), Efficient House Quality Mark, REQUEST, quality assured refurbishment (2010)
2001	KfW funds	CO ₂ Building Rehabilitation Programme
2001-2003	Investing in the Future Programme (R&D)	Research programme on energy efficiency retrofitting of existing buildings (EUR 15M)
2002	Energy Saving Ordinance (EnEV)	First approach (combining EnEv and WSOV) to stipulate the upgrade of U-values of individual building components. Requirement for new built ($U_w=1.4 \text{ W/m}^2\text{K}$), conditional requirement for windows in existing buildings ($U_w=1.7 \text{ W/m}^2\text{K}$).
2005-2011	5 th Energy Research Programme (R&D)	Focus on energy efficiency and innovative energy technologies. Merge of different research programmes under Energy Optimized Buildings (EnOB).
2006-2009	Klimazwei (R&D)	GEKKO is one of the 5 projects targeting energy efficiency in Klimazwei with the objective of developing a communication strategy for sustainable construction and refurbishment.
2006	Future Building (R&D)	Research initiative (ZukunftBau), including research on high-tech, energy efficient building components (e.g. windows) in cooperation with ift-Rosenheim.
2007	EnEV	No change in the requirement for windows in new built ($U_w=1.4 \text{ W/m}^2\text{K}$) and conditional requirement for windows in existing buildings ($U_w=1.7 \text{ W/m}^2\text{K}$).
2007	Trainings and certification	Passive house designer training programme and certification (Passive House Institute)
2009	EnEV	Upgrade for U-values of windows both in the new built and in the existing building stock ($U_w=1.3 \text{ W/m}^2\text{K}$).
2009	KfW funds	The KfW-Effizienzhaus 55 promotes houses using 55% of the maximum level primary energy use of the required level in EnEV2009; KfW-Effizienzhaus 70 promotes houses using 70% of the maximum allowed level of the required primary energy demand. For renovations, maximum U-value is given for windows or for glazings ($U_w=1.3 \text{ W/m}^2\text{K}$, $U_g=1.1 \text{ W/m}^2\text{K}$).
2011-2014	6 th Energy Research Programme (R&D)	Refocused resources of energy research towards energy efficiency with an earmarked budget of EUR 1.2 million out of EUR 3.5 million.
2012	EnEV	Upgrade of the requirements for the U-values in new buildings ($U_w=0.9 \text{ W/m}^2\text{K}$).

TABLE 2 POLICY INSTRUMENTS TO PROMOTE THE DEVELOPMENT AND DIFFUSION OF ENERGY EFFICIENT WINDOWS IN SWEDEN (1945-2010)

Modified source from Kiss & Neij, 2011 and Kiss, et al., 2012. Other sources: EU Directives (2002/91/EC, 2010/31/EU); Swedish Building Codes (BABS 1945, SBN 1975, BFS 1988, BBR12, BBR16, BBR18); Swedish Ordinance on Housing Financing (SFS 1974:946; SFS 2003:1204); (Boverket, 2009; Energimyndigheten, 2006, 2008, 2009a, 2009b)

Period	Policy instruments	Description / requirements
1945	First Building Code in Sweden	Official standards for windows: quality and design, but not energy performance.
1956-58	Subsidies and loans	For three-paned windows in newly built family-houses.
1975	R&D	Research programmes for improved energy efficiency (e.g. basic window physics: heat transmission and long-wave radiation)
1975	Building Code (SBN 1975)	Requirements for individual building components in specific climatic zones (north and south). For windows (including glazing, sash and frame) the requirement for U-value (U_w) was set at 2.0 W/m ² K in both zones.
1975-1993	Subsidies – tax exemptions	For refurbishment of the existing house stock and window replacements. The first tax relief was set for a period of two years; then it was extended in by 2-3 years at a time. NB: without requirements on windows' energy performance.
1985	Swedish P-label	Technical quality label, minimum requirement for the essential window characteristics.
1988	Building Code (BFS 1988)	Performance based building codes; the requirement for an average U-value (U_a) on the whole building envelope was set (for calculation method see BFS 1988). (It, hypothetically, allowed even higher U-values for windows than SBN 1975.)
End of 1980s	R&D	Increasing funding for long-term university-based research project – often in cooperation with the window and glass industry.
1992 and 1994	Technology procurement program	The requirement for energy performance was set at 0.9 W/m ² K in 1992, when no feasible solutions was developed, the requirement was raised to 1.0 W/m ² K in the second round (1994).
2004	Subsidies - tax exemptions	For replacement of windows with improved energy performance ($U_w \geq 1.2$ W/m ² K)
2006	Building Code (BBR 2006 / BBR12)	Based on the EBPD (2002), minimum standards on the energy performance of new residential buildings: south 110 kWh/m ² /year, north 130 kWh/m ² /year. More stringent requirements on the whole building envelope ($U_a=0.5$ W/m ² K). Alternatively, requirements for windows in smaller residential buildings (<100m ²): $U_w \leq 1.3$ W/m ² K.
2006-2007	Energy labelling	Voluntary scheme. A-G scale, where "A" is 0.9 W/m ² K and "G" is 1.5 W/m ² K.
2007	Specification for the passive house standard	Voluntary scheme. Adaptation of the German passive house standard for Swedish climate. ($U_w=0.9$ W/m ² K)
2009	Building Code (BBR16)	Revision of the required level of energy demand in different climatic zones and the extension of the number of zones to three; the requirement in the northernmost zone: 150 kWh/m ² /year. Upgrade of requirements in buildings with electric heating.
2009	Revision of the specification of passive house standard	It is mentioned in the specification that with the following revisions, the aim is to make the requirements more stringent, i.e. $U_w=0.8$ W/m ² K
2011	Building Code (BBR19)	Upgrade of BBR16: south 90 kWh/m ² /year, "middle" 110 kWh/m ² /year and the northernmost zone 130 kWh/m ² /year.

TABLE 3 POLICY INSTRUMENTS TO PROMOTE THE DEVELOPMENT AND DIFFUSION OF ENERGY EFFICIENT WINDOWS IN THE UK (1978-2010)

Modified source from Kiss, et al., 2012; Other sources: Building Regulations (1985, 1990, 1994, 2002, 2006, 2010); (BRE, 2009; DECC & EST, 2011; Elswijk & Kaan, 2008; EST, 2011; GGF, 2011; IEA, 2011a; Kilip, 2005)

Period	Policy instruments	Description / requirements
1978-1990	Home Insulation Scheme (grants)	Grants for energy efficiency upgrade, window replacement was excluded until the late 1980s (as draught proofing).
1980s	Building Regulations for England and Wales	First time energy efficiency requirements are addressed in regulations in the form of U-values (elemental method). No requirements set for windows.
1992	Information, trainings and certification	Foundation of Energy Saving Trust, relevant window development related programmes: Endorsed Advice Service and Training in more than 50 local information centres (1994), Energy Saving Trust Recommended label (2000).
1990	Building Regulation (BR)	Minimum requirement on the thermal performance of windows ($U_w=3.3 \text{ W/m}^2\text{K}$).
1994	Building Regulation	Upgrade of BR 1990 ($U_w=3.0 \text{ W/m}^2\text{K}$).
1994-2002	Energy Efficiency Standards of Performance	EESoP programmes targeting energy suppliers to provide energy efficiency measures in the residential sector and to SMEs.
1998	Value Added Tax (VAT)	VAT reduction from 17.5% to 5% for energy saving materials (including all insulation and draught stripping) for vulnerable households, from 2000 for all households.
1999	Energy labelling (BFRC)	Voluntary energy label for windows, issued by the British Fenestration Rating Council measuring the overall energy performance of windows in kWh/m ² /year. It also considers solar gains. Rating is from A to G; G corresponds with the min. requirement of BR.
2000	Energy labelling (EER)	Energy Efficiency Recommended sets requirements for windows in line with the energy label issued by BFRC.
2000-2012	Warm Front Scheme	Fuel poverty reduction programme providing public grants to vulnerable households for insulation (loft, draught proofing, cavity wall) and heating improvements.
2000-2010	Decent Homes Standard	A minimum standard for vulnerable households with regards to heating, weatherproofing and additional facilities with implementation guidelines (2004, 2006).
2002	Building Regulation	Upgrade of the BR: ($U_w= 2.0 \text{ W/m}^2\text{K}$). Energy labelling requirement.
2002-2008	Energy Efficiency Commitments (EEC1 and EEC2)	Programmes for energy suppliers to provide energy efficiency measures to households. Energy labelling becomes part of the EEC, C-labelled windows or better can be included.
2004	Research Council Energy Programme	Increasing focus on energy efficiency: in 2011, almost 10% of the total energy budget of RCEP was allocated to energy efficiency.
2004-2015	Landlords' Energy Saving Allowance	Tax allowance for private landlords to improve the energy efficiency of residential properties. On their tax return they can claim the cost of buying and installing energy saving measures, such as cavity wall and loft insulation, solid wall insulation (from 2005), draught proofing and hot water system insulation (from 2006) and floor insulation (from 2007).
2006	Building Regulation	Upgrade of BR, first time air tightness and thermal-bridging are integrated into BR. The energy labelling scheme is also incorporated: D label is accepted as an alternative to $U_w=1.8 \text{ W/m}^2\text{K}$.
2007	Technology Strategy Board	Business-focused organisation supporting investments in R&D and innovation by partnerships via "Innovation Platforms"; one of the six platforms is "Low Impact Buildings".
2007	Stamp Duty Relief for Zero Carbon Homes	Tax incentive for all new homes meeting zero carbon standard: no or reduced stamp duty for homes costing up to a certain amount respectively in excess to that amount.
2008	Code for Sustainable Homes (CSH)	Mandatory rating for new homes that goes beyond BRs. The highest performing level is zero carbon home ($U_w= 0.8 \text{ W/m}^2\text{K}$).
2008-	Carbon Emissions Reduction Target (CERT)	Programmes for energy suppliers to provide energy efficiency measures to households.
2008	Act on CO ₂ advice line	A 'one-stop shop' information service (EST) to make homes greener, incl. advice on energy saving, offers from energy companies (insulation) and financial support (e.g. Warm Front).
2009-2011	Pay As You Save (PAYS)	Pilot project of the Green Deal with the involvement of suppliers and end-users addressing energy efficiency retrofitting by subsidizing upfront costs and financing repayments with the savings made. Financing is linked to the property.
2009	Community Energy Savings Programme (CESP)	To improve energy efficiency standards and reduce fuel bills in low income areas through community-based partnerships. It is funded by energy suppliers and electricity generators carrying out tailor-made energy efficiency measures suited for each property.
2010	Building Regulation	Replacement windows shall comply with band C or better or U-value $1.6 \text{ W/m}^2\text{K}$.

Paper IV

Kiss, B., Neij, L. & M. Jakob (2012). Heat Pumps: A Comparative Assessment of Innovation and Diffusion Policies in Sweden and Switzerland. Historical Case Studies of Energy Technology Innovation in: Chapter 24, The Global Energy Assessment. Grubler A., Aguayo, F., Gallagher, K.S., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G. & C. Wilson. Cambridge University Press: Cambridge, UK.

Historical Case Studies of Energy Technology Innovation

CASE STUDY 4: HEAT PUMPS (SWEDEN & SWITZERLAND).

HEAT PUMPS: A COMPARATIVE ASSESSMENT OF INNOVATION AND DIFFUSION POLICIES IN SWEDEN AND SWITZERLAND

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AUTHORS' SUMMARY

The development and introduction of heat pumps provides an interesting illustration of policy influence and effectiveness in relation to energy technology innovation. Heat pumps have been supported by several countries since the 1970s as a strategy to improve energy efficiency, support energy security, reduce environmental degradation, and combat climate change. Sweden and Switzerland have been essential to the development and commercialization of heat pumps in Europe. In both countries, numerous policy incentives have lined the path of technology and market development. Early policy initiatives were poorly coordinated but supported technology development, entrepreneurial experimentation, knowledge development, and the involvement of important actors in networks and organisations. The market collapse in the mid 1980s could have resulted in a total failure - but did not. The research programmes continued in the 1980s, and a new set of stakeholders formed - both publicly and privately funded researchers, authorities, and institutions - and provided an important platform for further development. In the 1990s and 2000s, Sweden and Switzerland introduced more coordinated and strategic policy incentives for the development of heat pumps. The approaches were flexible and adjusted over time. The policy interventions in both countries supported learning, successful development and diffusion processes, and cost reductions. This assessment of innovation and diffusion policies for heat pump systems can be used to generalise some insights for energy technology innovation policy.

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1 INTRODUCTION

This paper presents the results and the policy programmes being applied to introduce and commercialize heat pumps, focusing on ground source heat pumps for residential space and hot water heating. Heat pumps are of interest since they have been supported by several countries since the 1970s as a strategy to improve energy efficiency, support energy security, reduce environmental degradation and combat climate change (IEA, 2008). Two countries, essential for the development and commercialisation of heat pumps in Europe, are Sweden and Switzerland. Since the early 1970s the number of installed heat pumps in Sweden and Switzerland has been rapidly growing, and as a result these two countries have the highest number of ground source heat pumps per capita and per land area respectively (EGEC, 2009). An important underlying reason may be that the two countries have had energy systems with similar characteristics, particularly a substantial supply of electricity for heating in the 1970s and 1980s. Heat pumps were therefore seen as energy efficiency measures rather than a means of substituting electricity for fossil fuels at the point of use.

Heat pump systems offer an energy efficient solution as they use 'free energy' (the solar energy stored in the earth) to provide heating, cooling, and hot water for homes. A heat pump moves heat from a low temperature heat source (i.e., bedrock, surface soil, water and outdoor air) to a higher temperature heat sink (i.e., the indoor space). Heat pumps are usually characterized by their heat sources (air, water and ground) and/or by the mediums between which they transfer heat (air-to-air, air-to-water, water-to-air, water-to-water). Ground source heat pumps (GSHPs) are a variant of either water-to-air or water-to-water heat pumps. Depending on the available land areas and the soil/rock types, GSHPs can be installed horizontally (soil), vertically (bedrock) or in a pond/lake. The most common heat pumps are motor-driven (electrically-powered or gas-fuelled). The ratio of thermal energy gained to electric power used is called the Coefficient of Performance (COP) and is in the order of 2.5 - 5. So if electrical space heating is replaced by a heat pump, considerable electricity will be saved. If a heat pump replaces an alternative heating system, savings will depend on the configuration of that system, including its conversion efficiency and distribution losses.

2 MARKET DEVELOPMENT OF GROUND SOURCE HEAT PUMPS

2.1 Market growth

The heat pump market took off during the 1980s following the oil crisis in the late 1970s (see Figure 1 and Figure 2). In Sweden, more than 900,000 heat pumps have been sold by Swedish heat pump companies since the early 1980s (SVEP, 2009). As of 2010, approximately 98% of the heat pumps sold serve the residential market, with most of the sales being small heat pumps (<20kW) for single family houses. Reports show that ground source heat pumps add value to properties (Boverket, 2008; Energimyndigheten, 2009). Until the mid 2000s, ground source heat pumps dominated market sales, constituting on average 45% of heat pumps sold each year with annual growth rates between 1993 and 2006 exceeding 30% (SVEP, 2009). Since 2000, the market share of air-to-air heat pumps has increased rapidly, and in 2008 air-to-air heat pumps consisted of more than 60% of total sales (see Figure 1). Exports have also represented a significant share of sales. According to interviews with manufacturers, in the mid 2000s approximately 40-50% of total Swedish production was exported.

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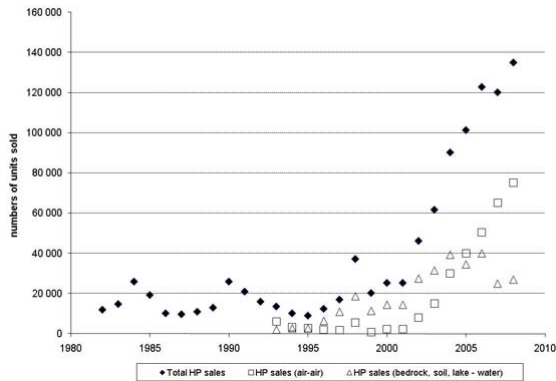


FIGURE 1. ANNUAL SALES STATISTICS OF HEAT PUMPS IN SWEDEN, 1980 – 2008, BASED ON DATA FROM THE SWEDISH HEAT PUMP ASSOCIATION (SVEP, 2007; NOWACKI, 2007). NOTES: HP = HEAT PUMPS. GROUND SOURCE HEAT PUMPS (INSTALLED IN SINGLE FAMILY HOUSES) PROVIDED 3.9% OF THE TOTAL DEMAND FOR SPACE AND WATER HEATING IN 1990. THIS HAD RISEN TO AROUND 10% OF TOTAL DEMAND IN 2008 (ENERGIMYNDIGHETEN, 2008; NOWACKI, 2007).

In Switzerland, more than 180,000 heat pump units have been sold since the 1980s (FWS, 2009). Most of the sales have been small heat pumps (<20kW) predominantly installed in new single family houses. The sales of ground source heat pumps increased rapidly in the 1990s and by the mid 2000s the market share of heat pumps among space heating and domestic hot water heating systems in new homes was around 75% (Rognon, 2006). In 2009, more than 20,500 ground source heat pump systems were sold, which shows an increase of almost 20% per year since 1993 (FWS, 2009).

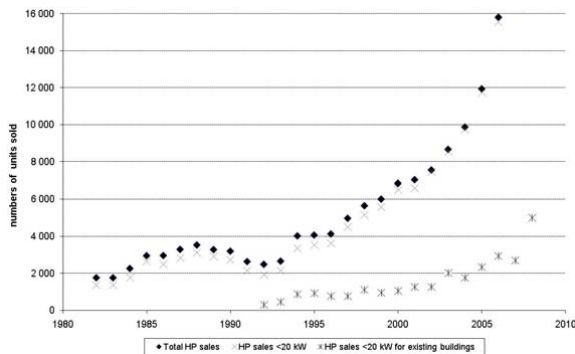


FIGURE 2. ANNUAL SALES STATISTICS OF HEAT PUMPS IN SWITZERLAND, 1982 – 2006 (ALL TYPES OF HEAT PUMPS), BASED ON DATA FROM THE SWISS HEAT PUMP PROMOTION GROUP (FWS, 2009; BASICS, 2002). NOTES: HP = HEAT PUMPS. GROUND SOURCE HEAT PUMPS PROVIDED 2.4% OF THE TOTAL DEMAND FOR SPACE AND WATER HEATING IN 2000 IN THE RESIDENTIAL SECTOR. THIS HAD RISEN TO AROUND 5.4% OF TOTAL DEMAND IN 2008 (BFE, 2010).

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2.2 Policy programmes

2.2.1 *Early Support*

To support technology and market development, both Sweden and Switzerland introduced broad-ranging policy programmes which emphasized R&D and the development of heat pumps based on available components (see Table 1 and Table 2). In Sweden, R&D programmes were complemented with subsidies, favourable loans, trainings and information campaigns. Long standing Swedish experience in water well drilling also supported the early development of the emerging market as it was applicable to borehole drilling used in the installation of vertical ground source heat pumps. In Switzerland, early support focused on conferences, training and testing activities. The policy incentives attracted many new heat pump manufacturers and installers to the market, and by the early 1980s, the number of heat pump installations increased rapidly. However, in the mid 1980s the price of oil was reduced and in Sweden, government subsidies for domestic heat pumps were terminated. As a result, the demand for heat pumps decreased significantly and the market collapsed in both countries. In 1984 there were about 130 heat pump companies (manufacturers, retailers and installers) in Sweden, most of which were small and working locally. In 1986 only a few companies were left (Florin, 1987; SPK, 1986; Törnell, 2007). Moreover, several types of heat pump installed in the early 1980s were registered as technically malfunctioning (Lindeberg, 1984). To support a more stable market development, new policy instruments were introduced in the early 1990s. The foundation for further trust was based on extended research activities focusing on aspects such as quality improvement, new compressor types, optimization of heat pump systems, the reduction of refrigerant volume, computer simulations as well as replacement of “freons” by HFC and natural refrigerants. These research activities were then complemented with instruments to provide more stable market development.

2.2.2 *Renewed support: Sweden*

In 1993, Sweden launched a technology procurement programme for ground source heat pumps. The objective of the programme was to stimulate the development and commercialisation of innovative and high quality heat pumps. The programme aimed to bridge the gap between buyers and manufacturers, helping buyers get products better suited for their needs, and helping manufacturers reduce risks associated with developing these products. The technology procurement programme worked from the end-use side. A specification outlining the requirements of advanced heat pumps was developed by a group of dedicated purchasers and specialists in cooperation with Swedish Agency for Economic and Regional Growth (NUTEK). The specification required a heat pump that was 30% more efficient and 30% cheaper than the existing models on the market, met high quality and reliability standards, and did not allow products using CFCs or HCFCs (stratospheric ozone depleting chemicals). A competition was announced in which manufacturers were invited to enter prototypes with features that met the requirements of the specification. The buyers’ group guaranteed that at least 2,000 units would be purchased of the winning model. To ensure credibility, third party testing of the prototypes and the whole heating system was performed. (Initial difficulties in replacing CFCs / HCFCs led to a new research programme being launched in the mid 1990s).

To support a stable market development of improved heat pumps, the procurement programme was combined with additional policy incentives, such as investment subsidies, information campaigns and evaluations. In all, 25% of the procurement budget was earmarked for the evaluation of heat pump

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installations through a test and certification programme (free tests for participants, and certification of the quality and technical performance of the heat pumps). Evaluation results were presented in articles and seminars. A further 50% of the procurement budget was allocated to information activities, including information campaigns, brochures and articles (Miljöstyvningsrådet, 2008). The procurement programme boosted demand for heat pumps with sales doubling between 1995 and 1996. Between 1996 and 2006 the number of installations of bedrock, soil and lake heat pumps increased at an average of 35% per year (SVEP, 2007). The increase in installations of heat pumps in the late 1990s and early 2000s was further supported by additional government subsidy programmes (1998-99, 2001-03 and 2006-10). In 2005, a quality label for heat pumps was introduced (P-label) as well as a standard on the installation of the geothermal system (Normbrunn-97), including requirements for the borehole, equipment, and competence of the drillers which was also assured by a voluntary certification scheme and new certification courses for installers.

TABLE 1. POLICY INSTRUMENTS AND MAJOR EVENTS RELATED TO HEAT PUMP DEVELOPMENT IN SWEDEN, 1974-2008.

NOTES: SEE TABLE FOOTNOTES FOR ACRONYMS. SOURCES: ÅSTRAND ET AL., 2005; NILSSON ET AL., 2005; ENERGIMYNDIGHETEN, 2007B; ENERGIMYNDIGHETEN, 2007A; ENERGIMYNDIGHETEN, 2002B; NEIJ AND ÖFVERHOLM, 2001; ENERGIMYNDIGHETEN, 2002A; SFS1997:635, 1997; NOWACKI, 2007; SVENSSON AND HAVSJÖ, 2006; SVEP, 2007; TÖRNELL, 2007.

PHASE	POLICY INSTRUMENTS AND MAJOR EVENTS
1974-1989 Increasing awareness of energy and environment issues	1974: 1 st seminar on heat pumps for researchers, authorities, builders and real estate owners (BFR, Vattenfall, NUTEK, SP) 1973-1974: International Energy Agency's heat pump group 1975: 1 st energy research programme (government support) 1970s: Industry and public funding for demonstration projects (Vattenfall, AGA Thermia, BFR, etc.) 1977-1985: Investment subsidies and loans for households (1977-79; 1979-80; 1980-81; 1981-83; 1983-84; 1984-85) 1979-1985: Energy Prototype and Demonstration Programme: energy guidance training and dissemination of information (municipalities) 1980s: Start of testing activities (SP and industry) 1987: CFC phase out, Montreal Protocol (government commitment)
1990 – 2010 The success story	1990- Continuous research programmes (government support) 1990-1995: Technology procurement programme (NUTEK) including investment subsidies and information campaigns late 1990s: 1 st quality label (P-label) for GSHPs (SP) 1998: Introduction of energy advisory offices (municipalities) 1998-99: Subsidies for residential houses to convert from electric heating systems to other energy sources (1998-99; 2001-03; 2006-10) 2006: 1 st Swan eco-label for heat pumps (criteria development from 1998 with multiple stakeholder involvement)
BFR: Swedish Building Research (Byggnadsförskningsrådet), after 2001 the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas) was formed and included BFR NUTEK: Swedish National Board for Industrial and Technical Development (from 1998, the Swedish Energy Agency) SP: Technical Research Institute of Sweden (Sveriges Tekniska Forskningsinstitut)	

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2.2.3 *Renewed support: Switzerland*

In Switzerland, a ten year programme called “Energy 2000” was launched in 1990 by the Swiss Federal Office of Energy, followed in 2000 by the “Swiss Energy” programme. These programmes aimed at increasing the use of renewable energy and improving energy efficiency. The use of heat pumps was considered one of the promising pillars to meet quite ambitious goals. In addition to the public financed initiatives of the early 1990s, several measures financed by the private sector were launched. To a large extent, the public and private incentives were coordinated and complemented each other (Rognon, 2008; Rognon, 2006). Policy measures were also adjusted over time to support continuous technical, institutional and economic development. Moreover, several strategic and organisational measures were taken to coordinate the initiatives to support heat pumps. At the Swiss Federal Office of Energy, a position was created to coordinate research, development, technology transfer and market development of heat pumps (Rognon, 2006). In 1993, the Swiss Heat Pump Promotion Group (FWS) was constituted to coordinate market activities. This group involved heat pump producers, distributors, installers, some leading electricity utilities, sector and cantonal authorities and a professional marketing company (Zogg, 2008).

To further support technology development and quality control in the 1990s, a test centre was created in 1993 in Winterthur-Töss. After some scepticism and reluctance, heat pump companies agreed to test their products, which increased confidence in the technology. In 1993-1995 a public subsidy programme was launched for investing in heat pumps in existing buildings. In relative terms, sales increased significantly (by a factor two), but after the subsidy period sales declined again. Although in absolute terms, the subsidy programme did not have a tremendous impact (about 800 units were sold per year), it built up trust in the heat pump technology and was seen as a catalyser for further market development (Rognon, 2006). In 1996, marketing activities were reinforced and the first heat pump exhibition took place. In 1997, subsidy programmes and special electricity tariffs were launched by some utilities, and professional education and training were also improved. In 1998, the Swiss Retrofit Heat Pump Competition Program was launched to develop high efficiency and competitive heat pumps for heating domestic hot water. This programme brought together manufacturers, universities and other actors and was important for creating a common understanding of technology and market development.

In 1997, the canton of Zurich legally restricted the share of non-renewable energies for heating and hot water purposes in new buildings to 80% of the allowed useful energy demand per m². Subsequently this requirement was implemented by most of the other Swiss cantons. The requirement could be satisfied either by additional insulation, by using wood or solar energy, or by using heat pumps. As electrically driven heat pumps were a cost-effective option, this legal measure represented a strong policy incentive for the deployment of heat pumps. In 1997, to support energy efficiency and renewable energy in residential buildings, the concept of “Minergie house” was introduced. Minergie is a voluntary standard whose requirements can also be met by using heat pumps. To support product quality, in 1998 the DACH label was introduced for heat pumps. In 2001, the first DACH labels were also given to drilling companies.

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TABLE 2. POLICY INSTRUMENTS AND MAJOR EVENTS RELATED TO HEAT PUMPS IN SWITZERLAND, 1973-2008 (ROGNON, 2008; ROGNON, 2006; ZOGG, 2008). NOTES: SEE TABLE FOOTNOTES FOR ACRONYMS.

PHASE		POLICY INSTRUMENTS AND MAJOR EVENTS
1973 - 1989	Awareness of energy and environment issues	1974: 1 st guidelines of the Swiss Association for Refrigeration 1980: 1 st conference on heat pump technology in Switzerland 1980s: 1 st heat pump testing facility (EPFL) 1981/82: Start of heat pump system field testing (NEFF and SFOE) 1983: Meeting on simplification of approval procedure (SFOE and authorities)
1990 - 2010	The success story	1990-1992 First steps 1990: Launch of Energy2000 (SFOE) 1992: Heat pump promotion programme (Energy2000) 1993-1995 Bundling of activities 1993-1995: Subsidy for heat pumps in existing buildings 1993-1996: Handbooks for better heat pump installations 1995: FAWA - heat pump systems, field testing (SFOE) 1996-2000 Consolidation 1996: 1 st heat pump exhibition (trade fair for the general public) 1997-1998: Subsidies supported by some electricity utilities 1997: Standards including that max. 80% of heat and hot water of new buildings could be covered by non-renewable energies (Canton of Zurich) 1998: Heat pump retrofit programme and competition (R&D and subsidies) 1998: Creation of heat pump quality label DACH (Germany, Austria, Switzerland) 2001-2005 Industrialisation 2000: Launch of Swiss Energy (follow-up programme of Energy 2000) 2001: DACH label for drilling companies 2006-2010 Path to independence 2006: Regular 3 day training programme for installers
AWP: Swiss Working Committee of Manufacturers and Distributors (Arbeitsgemeinschaft Wärmepumpen) EPFL: Swiss Federal Institute of Technology in Lausanne (Ecole Polytechnique Fédéral de Lausanne) FAWA: field testing of heat pump systems (Feldanalyse Wärmepumpen) FWS: Swiss Heat Pump Promotion Group (Fördergemeinschaft Wärmepumpen Schweiz) NEFF: private national energy research fund, sponsored by oil, gas and electricity utilities (Nationaler Energieforschungs Fonds) SFOE: Swiss Federal Office of Energy WPZ: Heat Pump Test Centre in Winterthur-Töss		

3 EVALUATION OF INNOVATION & DIFFUSION POLICIES

Over time, numerous policy incentives have lined the path of heat pump technology and market development in Sweden and Switzerland. In both countries, the early policy initiatives were poorly coordinated but supported technology development, knowledge development, the involvement of important actors, and market formation. The market collapse in the mid 1980s could have resulted in a total failure – but did not. The research programmes, continuing in the 1980s, and the set of stakeholders and networks formed in the early years, i.e., public and private funded researchers, authorities and institutions, provided an important platform for further development. The influence of informal “advocacy coalitions” (Sabatier and Jenkins-Smith, 1993) supported further development of heat pumps and new policy initiatives (Nilsson et al., 2005).

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In the 1990s and the 2000s both Sweden and Switzerland introduced more strategic, coordinated and flexible policy incentives for the development of heat pumps. The focus was on knowledge development, networking, and market formation, but also on quality control, credibility and legitimacy. R&D, testing & certification was developed in close cooperation with additional strategic market initiatives. Subsidies were introduced as a strategic incentive and catalyst in the 1990s in both Sweden and Switzerland; the role of later subsidies in Sweden is, however, more uncertain. Both countries had a focus on networking, which encouraged important processes of learning. International networking through IEA research may have also played an important role for international learning and spillovers.

3.1 Technology developments

Both in Sweden and Switzerland, continuous government and private R&D support was essential for the development of heat pumps. The R&D programmes supported technical development throughout the boom in heat pump sales in the early 1980s, the market collapse in the mid 1980s and the reinforcement and consolidation of the market in the 1990s and 2000s. Moreover, R&D support extended to the infrastructure in terms of boreholes and drilling processes. In Switzerland, early R&D support in borehole modelling and computer simulation in combination with prior experience in water drilling was essential for heat pump development. In Sweden, less R&D was needed and the development relied on existing experience in water drilling. Both countries developed a leading international position in drilling and boreholes in the early years.

Another key initiative for supporting technology development was the development of test facilities in the 1970s (in Switzerland) and 1980s (in Sweden). In the 1990s the test facilities were considered a vital element for providing reliable and high quality heat pumps. The requirements of testing provided essential quality control and support of the 1990s subsidy programmes. Consequently, the poor reputation of heat pumps from the 1980s could be overcome and credibility re-established. Quality labels were introduced in Switzerland in 1998 and in Sweden in 2005. Quality labels were then also given to drilling companies and drilling installations reflecting the competence of drillers. In Switzerland, the test centre in Winterthur-Töss measured an increase of 20-36% in heat pumps' performance (COP) and energy efficiency between 1992 and 2002 (WPZ, 2001). In Sweden, the Technical Research Institute of Sweden measured 13 - 22% improvement in heat pumps' performance (COP) between 1995 and 2005 (SVEP, 2007).

3.2 Market developments and the involvement of actors

The main driver of the early market development of heat pumps in the 1970s and 1980s was high oil prices. In both countries additional policy instruments accentuated this market demand. In Sweden, the focus was on demonstration programmes and subsidies; the subsidies were, however, fragmented and uncertain. In Switzerland, incentives for market development also addressed networking. In the beginning, market actors involved in both the sale and production of heat pumps were small and working locally. As the market grew in the 1980s the number of actors increased; relevant actors included heat pump manufacturers, retailers, driller and installation suppliers, research organizations, authorities, certifying bodies and test institutes. The collapse of the heat pump market in the mid 1980s, as a result of cheap heating oil (and a subsidy withdrawal in Sweden), reduced the number of heat pump manufacturers and retailers as well as maintenance personnel in both markets. This had severe

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consequences not only on the sales of new heat pumps but also on the maintenance of the installed ones.

In the early 1990s, as a result of increasing concerns about environmental pollution as well as strong lobbying from the advocacy coalition, both Sweden and Switzerland decided to strengthen the heat pump market. In Sweden, a well-coordinated market transformation programme was launched based on a technology procurement programme in combination with test and certification programmes, subsidies and massive information activities. The procurement not only provided high quality technology and substantial market support but also essential interactions among actors. In Switzerland, strategic research activities, subsidies as well as education, training and networking were introduced. As in Sweden, the subsidies were to have a catalytic effect on the market, but were also limited in time. The establishment of organisations for coordination and networking was also important. The programmes in both countries should not be seen in terms of individual policy instruments but rather as strategic and coordinated programmes to re-ignite the market. As a result of these programmes the market for heat pumps took off again. Industrial production ramped up and the number of manufacturers stabilized. In Sweden, “one-stop-shop contractors” were formed – taking responsibility for the entire heat pump system (design, installation and start-up).

In the 2000s, the support of heat pumps continued in both Sweden and Switzerland. In Sweden, market development was, again, supported through subsidies. However, uncertainties regarding the duration and magnitude of these subsidies undermined manufacturers’ long-term investments in technology development. As a result, between 2000 and 2003, 26% of the ground source heat pumps installed in Sweden were reported to have some imperfections (Snaar, 2005). In Switzerland, the market development of heat pumps in the 2000s was driven by law (maximum share of non-renewable energy for heating) and by voluntary standards (“Minergie” houses). The approaches in Sweden and Switzerland, i.e., subsidies as well as legal requirements and voluntary standards, effectively supported strong market growth in the late 1990s and 2000s. However, the subsidies applied in Sweden over the years have contributed to large government expenditures, in comparison with the use of mandatory and voluntary standards to direct industry expenditure in Switzerland.

3.3 Cost developments

The policy programmes and their effect on increased production and sales of heat pumps have provided opportunities for cost reductions over time. In Switzerland, cost reduction is reflected in the decreasing consumer prices of ground source heat pumps for new single family houses (see Figure 3). During the past three decades, costs have been reduced by more than a factor two. In the early 1980s, the total cost of heat pump systems was almost twice as high as for fossil fuel heating systems; currently heat pumps are cost-competitive. Important drivers of cost reduction have been economies of scale (mass production), not only for heat pumps as such, but also for borehole drilling (for instance, capital costs of drilling systems could be distributed to more clients), and continuous technology improvements. Moreover, parts of the heat pumps are now imported at a lower cost than when produced in Switzerland.

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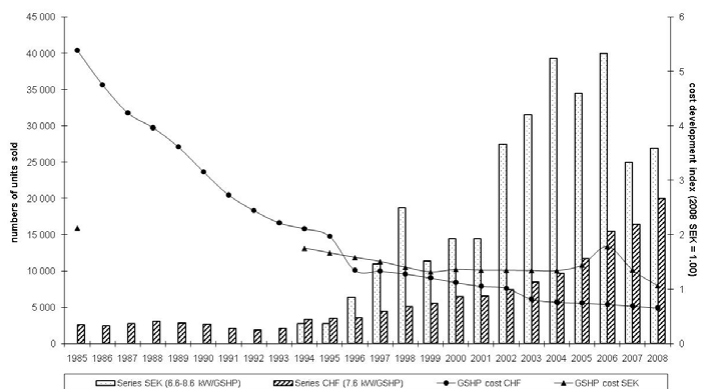


FIGURE 3. NUMBER AND COST OF HEAT PUMPS INSTALLED IN SWEDEN AND SWITZERLAND. NOTES: COSTS INCLUDE THE COST OF HEAT PUMP UNITS AND EXCLUDE COSTS RELATED TO INSTALLATION AND DRILLING. IN SWEDEN, THE SALES FIGURES ARE BASED ON DATA FROM THE SWEDISH HEAT PUMP ASSOCIATION (SVEP, 2007); COST FIGURES IN SWEDISH KRONA (SEK) ARE BASED ON DATA FROM THE SWEDISH ENERGY AGENCY (ENERGIMYNDIGHETEN, 1999; ENERGIMYNDIGHETEN, 2002B; ENERGIMYNDIGHETEN, 2004; ENERGIMYNDIGHETEN, 2006), THE SWEDISH CONSUMER AGENCY (KONSUMENTVERKET, 1986; KONSUMENTVERKET, 2004) AS WELL AS ONLINE TEST MAGAZINES (LAGERGREN, 1995; LAGERGREN, 1999) AND COMPANY PRODUCT SHEETS. IN SWITZERLAND, SALES FIGURES ARE BASED ON DATA FROM BASICS (2002) AND FWS (2009); COST FIGURES IN SWISS FRANCS (CHF) ARE FROM FWS STATISTICS. THE BASE YEAR FOR THE COST INDEX IS 2008, THE BASE CURRENCY IS SEK. PRICES OF SWISS HEAT PUMPS IN CHF ARE CONVERTED INTO SEK USING ANNUAL AVERAGE MARKET EXCHANGE RATES (WWW.OANDA.COM). IN 2008, THE AVERAGE PRICE OF A GROUND SOURCE HEAT PUMP UNIT (6.6 - 8.6 kW) IN SWEDEN AMOUNTED TO AROUND 53,000 SEK (8,140 USD). IN SWITZERLAND, COMPARABLE PRICES FOR HEAT PUMP UNITS OF 7.6 kW WERE AROUND 7,800 CHF (47,000 SEK OR 7,230 USD).

In Sweden, as in Switzerland, consumer prices of ground source heat pumps have reduced over time; however, the trend differs in the two countries. In Sweden, the consumer price merely slightly decreased between 1985 and 1995; despite several drivers of cost reduction (i.e., incremental technology improvements, standardization and industrialization of production) it then remained fairly stable until the mid 2000s. As Figure 3 shows, the cost reduction has been stronger in Switzerland over the years, however, the consumer price level has been lower in Sweden until the beginning of 2000s. The reason for the constant consumer prices in Sweden could include limited competition of contractors and fragmented and uncertain subsidies; however this has not been verified by interviews carried out as part of this study. The price increase in 2006 can clearly be related to the introduction of a subsidy in an already saturated market. Another explanation may be that the components of the Swedish heat pumps are all manufactured in Sweden, whereas manufacturers in Switzerland import most of the components and claim this to be a major source of cost reductions.

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The cost reductions over time observed in Figure 3 are shown in Figure 4 as a learning curve which expresses capital or investment costs as a function of cumulative deployment. The characteristic declining cost profile is clearly seen, as is the contingency of the rate of decline and stabilisation on market conditions (e.g., Swiss and Swedish differences) and technological maturity.

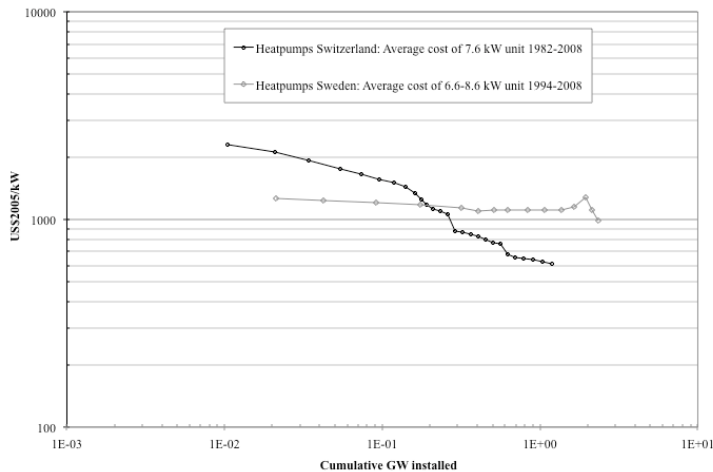


FIGURE 4. COST OF HEAT PUMPS AS A FUNCTION OF CUMULATIVE EXPERIENCE: LEARNING CURVES. NOTE: LOG-SCALE X AND Y AXES.

4 INSIGHTS FOR INNOVATION AND DIFFUSION POLICIES

Assessment of the policy incentives applied in Sweden and Switzerland to support the development of heat pumps and their emerging market can be used to illustrate some important characteristics of policy learning.

First of all, this case study shows the need for long term and continuous support for energy technology innovation. The first attempts to influence the introduction of a new technology may fail, thus continuous support is needed to overcome initial shortcomings. The technology lifecycle, from innovation through to widespread diffusion, takes time. In the case of heat pumps, early government support was introduced in the 1970s but it was not until the 2000s that a major market increase was seen and production was industrialised. Over time, the combination of policy instruments may have to change and the approach used by the government needs to be flexible. Initially, policy may allow and support entrepreneurial testing, but this should be developed into stable strategies over time to allow industry to make long-term investments in standardised products.

Secondly, policy interventions need to consider both the development of the technology and its emerging market and actors. In other words, R&D is necessary but not sufficient. Market formation also

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requires policy incentives that support learning processes related to the use of the products. Moreover, various support for building and strengthening actor-networks is essential for improving strategic integration and learning to ensure feedback and spillover effects.

Thirdly, testing and certification processes are needed not only to support technical quality but also credibility and legitimacy. R&D initiatives as well as subsidies require testing and certification to support a stable market development. Due to an emphasis on quality assurance in the early 1990s, the market of heat pumps started to grow again after having collapsed in the mid 1980s. By establishing a system for quality assurance, both Sweden and Switzerland created reliable products and a high level of public acceptance.

5 FURTHER READING

For an international review of the technical development of heat pumps and the Swiss examples and contribution to this development, see Zogg, 2008. Rognon (2006; 2008) provide a good insight into the role of the state in the promotion of heat pumps on the market. For an overview of the Swedish heat pump market development, see Törnell, 2007.

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Paper V

Kiss, B. (2013). Exploring transaction costs of passive house-oriented renovations.
Submitted.

V

Exploring transaction costs in passive house-oriented retrofitting

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Abstract

In order to tap the energy saving and climate mitigation potential of the building sector, transaction costs of implementing energy efficient technologies and concepts need to be better understood and ultimately reduced. The objective of this paper is to identify and analyze the nature and scale of transaction costs resulting from the application of the passive house concept in energy efficient renovations. In addition, it explores measures to promote learning and knowledge development as potential strategies to reduce transaction costs. It focuses on transaction costs borne by building owners and building developers in the planning and implementation phases of a passive house-oriented renovation in Sweden. Results reveal three main sources of transaction costs: due diligence, negotiations and monitoring. The analysis shows that transaction costs are non-negligible and for individual cost sources can be 200% higher than for conventional renovations. To reduce these high transaction costs, various strategies such as study visits, demonstration projects, new forms of meetings and new channels of (written) information were found.

Key words: Transaction cost, energy efficiency, passive house renovation

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1 Introduction

The building sector in Europe accounts for approximately 40% of the total energy use and 36% of all energy-related CO₂-emissions (BPIE, 2011). In order to meet the ambitious EU “20-20-20” target by 2020, energy efficiency in buildings needs to be improved². A major part of the European building stock was built when building energy performance requirements were scarce (BPIE, 2011), thus the need for energy efficient renovation in existing buildings is vast. Numerous building retrofit projects have demonstrated that energy efficiency improvements are not only technically feasible and socially favoured, but also provide cost-effective reductions of primary energy and greenhouse gas emissions (Ürge-Vorsatz, Harvey, Mirasgedis, & Levine, 2007; Ürge-Vorsatz, Koepfel, & Mirasgedis, 2007). The potential energy savings for heating in high performance retrofitting, for example by applying the passive house concept³, is as high as 70-92% (Ürge-Vorsatz et al., 2012). Despite many good examples, energy efficient retrofitting is still not a common practice due to a number of barriers⁴.

Recent studies have shown that high investment costs and unforeseen transaction costs are two of the main barriers to energy efficiency in buildings (Levine, et al., 2007; WBCSD, 2009; Ürge-Vorsatz, et al., 2012). Initial investment costs of energy efficient buildings can be 4-16% higher than for conventional buildings (Audenaert, De Cleyn, & Vankerckhove, 2008) and transaction costs have been estimated to be as high as 20% of the investment cost (Ürge-Vorsatz, et al., 2012). In all, the high upfront investment costs and transaction costs hinder the implementation of energy efficient technologies in the building sector and prevent real estate developers from entering the energy efficiency market (Lee & Yik, 2002).

The passive house concept is a standard for state-of-the-art energy efficient buildings. Since 1990, the introduction of the first passive house in Kranichstein (Darmstadt, Germany), the number of passive houses has dramatically increased, and at the end of 2012 the estimated number of passive buildings worldwide reached up to 40 000 (IPHA, 2012). The additional investment cost of newly built passive houses has been in the range of 0-17% of the total construction costs (Audenaert, et al., 2008; Hermelink & Hübner, 2003; Schnieders & Hermelink, 2006). Nevertheless, literature on the passive house experience shows that the high investment costs of energy efficient buildings can be reduced over time. Since the 1990s, the additional costs to meet the Passive House standard for new buildings have been reduced by a factor of 5-7. This is due to the increased availability of passive house technologies, such as improved insulation, energy efficient windows and highly efficient ventilation systems and due to accumulated experience in passive building methods (Feist, 2006; Harvey, 2009). In Germany, Austria and

² The “20-20-20” initiative is based on the EU’s energy goals, adopted by the Council in 2007. They aim to reduce GHG emissions by 20%, increase the share of renewable energy to 20% and improve energy efficiency by 20% (BPIE, 2011).

³ The passive house concept is based on greatly improved thermal performance of the building envelope (high insulation and air tightness levels) coupled with a mechanical ventilation system with efficient heat recovery. As heat energy is needed only occasionally, the heating system can be kept very simple, e.g. electric heating or a heat pump (see e.g. Feist, Schnieders, Dorer, & Haas, 2005; Hastings, 2004; Schnieders, 2003; Schnieders & Hermelink, 2006).

⁴ Barriers to energy efficiency in the building sector include, for example, imperfect information, lack of knowledge and barriers more specifically related to the introduction and development of (new) energy efficient technologies such as cumbersome (regulatory, administrative and planning) processes, uncertainty and risk, limited access to technologies, split incentives, high upfront investment costs, limited access to capital, lack of monitoring and transaction costs (Carbon Trust, 2005; Levine et al., 2007). Some of these barriers can be defined as market failures (Levine, et al., 2007; Sutherland, 1991).

Switzerland, with a high number of passive houses, the average additional cost of building a passive house went down to 5-8% of the conventional construction cost (Passive-On, 2007; PHI, 2012; Ürge-Vorsatz, et al., 2012). In Sweden, the additional investment cost of low-energy buildings (of passive house standard) is estimated to be less than 10% of conventional building costs (Blomsterberg, 2009).

In recent years, the passive house concept has also been applied to the retrofit of existing buildings. An example from Germany shows that the cost of multi-family dwelling retrofits according to the passive house standard (with >90% energy savings) can be 27% higher than conventional renovations (Haus der Zukunft, 2007). Other studies show that additional costs of energy-related renovation can add up to 35-50% of the total retrofitting costs (Enseling & Hinz, 2009; IBB, 2010). In the first passive house-oriented retrofit project in Sweden (Brogården), approximately 30% of the total retrofit costs were energy-related (Hellberg, 2012). To the author's knowledge, no studies have been devoted so far to analyse transaction costs related to renovations based on the passive house concept. The knowledge gap is very explicit when reviewing the literature on transaction costs associated to energy efficiency technologies (details in Section 2). In order to find the most feasible approaches to reduce transaction costs of energy efficient renovations in the future, transaction costs must be better understood.

This study aims to identify the nature (origin) and scale (order of magnitude) of transaction costs in passive house-oriented retrofit projects. Further, it aims to explore the potential for reducing these transaction costs by identifying approaches promoting learning and knowledge development. Such approaches include actors' strategies, i.e. leadership, procurement, training and meeting platforms, demonstration practices, community meetings, educative seminars and newsletters. These approaches are also of interest in terms of designing and supporting future policies related to the passive house technologies.

In order to explore transaction costs and provide empirically contextualized evidence for the origin and the scale of transaction costs, case study methodology was applied to Brogården, the first passive house-oriented retrofit project in Alingsås (Sweden). The case was explored based on a review of the literature describing the case and 14 semi-structured deep interviews with actors involved in the renovation project. The focus of the interviews was on the presence, nature, scale⁵ and attribution of transaction costs in the different phases of the renovation process. In this study, special attention is given to the building owner and building developer in the planning and implementation phases. The Brogården case was chosen because it is the first passive house-oriented renovation in Sweden and the experience yielded by this case study is applicable to an additional 350 000 similarly constructed apartments in many Swedish cities, representing almost 8% of existing apartments (Berggren, Janson, & Sundqvist, 2009; SCB, 2010).

The outline of this paper is as follows: Section 2 provides the key analytical components for the study: a review of transaction costs in the energy field and overview of the case study. Section 3 provides the research results, highlighting the nature and scale of transaction costs. Section 4 discusses approaches promoting learning and knowledge development for energy efficient retrofitting as potential strategies to reduce transaction costs. Conclusions are drawn in Section 5.

⁵ The scale of transaction costs are estimates reflected in additional resources, such as time (hours) and/or money (SEK), which are put into the project due to passive house renovation and thus surrounded by high uncertainty.

2 Analytical framework

2.1 Transaction costs

The concept of transaction costs originates from Coase (1937) and has been further developed in the framework of New Institutional Economics (NIE) (Williamson, 1993, 1996)⁶. Transaction cost analysis is a fundamental element of NIE. It assesses activities in the economic system, such as how they are organized and carried out, and what effects they have on the performance of the projects and/or the actors involved through transactions with involved market actors (Commons, 1931). These transactions are often based on imperfect information, bounded rationality and lack of monitoring (Douglass, 1990; Ménard, 2004; Selten, 1990). Transaction costs are related to financial operations, they are costs not directly involved in the production of goods or services, but unavoidable and often unforeseeable costs emerging from contracting activities essential for the trade of such goods and services (Coase, 1960). In the field of technology change, transaction costs are often referred to as unmeasured costs that prevent the adoption of new technologies. In this context, transaction costs are also understood as costs occurring ex-ante to the arrangement and implementation of technologies and ex-post to their monitoring and enforcement (Matthews, 1986). Regarding the specific case of energy efficiency, imperfect information may hinder market actors' purchase or installation of energy efficient technologies, and thus can decrease the financial gains from improved energy efficiency (Sanstad & Howarth, 1994; Sioshansi, 1991).

Transaction costs have been analyzed in the field of energy efficiency and have mostly been characterized by their origin (nature) and order of magnitude (scale). Transaction costs of energy efficient technologies originate throughout the life-cycle of projects. Transaction costs can be categorized as costs of a) due diligence (search for and assessment of information), b) negotiation, c) approval and certification, d) monitoring and verification and e) trading (Mundaca, Mansoz, Neij, & Timilsina, 2013). Transaction costs associated with the implementation of energy efficiency projects typically arise as a result of searching for and assessing information, project preparation, finding partners, contracting, persuading, negotiating and coordinating with partners, decision-making, implementing and following-up investment actions, for example, through maintenance or validating data. For more information on transaction costs on searching for and assessing information see Björkqvist & Wene (1993), Hein & Blok (1995), Mundaca & Neij (2007), Sanstad & Howarth (1994), Sathaye & Murtishaw (2004), Sioshansi (1991), for project preparation, see Bleyl-Androschin, Seefeldt & Eikmeier (2009), for finding partners, contracting, and persuading, see Mundaca (2007), for negotiating with and coordinating partners, see Bleyl-Androschin, et al. (2009), Mundaca (2007), Ostertag (1999), for decision-making, see see Björkqvist & Wene (1993), Hein & Blok (1995), for implementing and following-up investment actions, see Bleyl-Androschin, et al. (2009), Hein & Blok (1995), Mundaca (2007), Qian, Chan & Choy (2013), Sathaye & Murtishaw (2004), for maintenance, see Ostertag (1999) and for validating data, see Mundaca (2007). The research focus of transaction costs, according to existing literature, has been mostly on industry, i.e. energy intensive or energy companies involved in energy saving programmes (Hein & Blok, 1995; Joskow & Marron, 1992; Mundaca & Neij, 2006; Ostertag, 1999). Studies focused on the residential sector include energy companies implementing energy efficiency measures in

⁶ NIE incorporates the theory of institutions into economics with the purpose of explaining institutions, including their evolution, performance and impact over time. (Institutions, in this case, are defined by (North, 1990)).

households (Bleyl-Androschin, et al., 2009; Mundaca, 2007; Mundaca & Neij, 2007) or end-users investing in energy efficient household appliances (Björkqvist & Wene, 1993; Sathaye & Murtishaw, 2004). Only a few studies identify the order of magnitude of transaction costs (see e.g. Björkqvist & Wene, 1993; Bleyl-Androschin, et al., 2009; Mundaca, 2007).

Regarding the scale of transaction costs, several studies have attempted to provide empirical estimates for the building sector. The scale of transaction costs is most often expressed in proportion (%) to the total (investment) cost, but sometimes in monetary terms (e.g. SEK) or in work load (e.g. time, hours) (Björkqvist & Wene, 1993). For instance, transaction costs for lighting technologies are estimated to be 10%, for improved cavity wall insulation 30%, and for energy efficiency measures carried out by ESCOs in the residential sector in the range of 20%-40% (Easton Consulting, 1999; Mundaca, 2007). In Sweden, transaction costs related to energy efficiency in the building sector have been estimated to be 20% of the total investment costs (Ûrge-Vorsatz, et al., 2012). Estimates of transaction costs are subject to uncertainty due to the performance of the technology, accountability, reliability and accuracy of data sources and the methods of monitoring and quantifying transaction costs (Mundaca, et al., 2013).

In this study, transaction costs associated with application of the passive house concept were assessed in relation to the life-cycle of the building project, including the planning, implementation, operation and follow-up phases. Transaction costs considered were those identified in earlier studies described above. Transaction costs have also been attributed to relevant actors.

2.2 Case Study: Brogården passive house renovation

Brogården is the first passive house renovation project in Sweden. The 16 building blocks include 300 apartments (19 500 m²) and were built in 1971-73 in Alingsås, a city of 40 000 inhabitants located in the western part of Sweden. Brogården is one of the districts of the “One million programme” in Sweden; one million apartments were constructed during 1965-1975 to meet a high demand for housing.

The renovation of Brogården is being implemented in six stages over six years (2008-2014), each stage having a life-cycle of three phases: a) planning, b) implementation and c) operation and follow-up. The first stage (two buildings) serves as a demonstration for the rest of the stages. Each stage includes two to five buildings; the stages are typically overlapping. The planning phase of the Brogården renovation project included feasibility studies and conceptual design, based on which project requirements, targets and technical suggestions were formulated and tendered⁷. The planning phase, in a broad sense, lasted for six years, counting from the first time Alingsåshem started to plan the renovation of Brogården. In a strict sense, the actual planning took a year and a half (2005-2007), from the pre-study to procurement. The procurement lasted approximately for half a year (2006-2007). The activities and results originating from the planning phase are essential as they greatly influence the life-cycle of the entire renovation project in all six stages. The implementation phase covers activities related to construction and installation, led by the building developer, for instance detailed planning of the building process

⁷ The procurement process, in general, includes the preparation of tender calls, assessment and approval of the applications and preparation of the contracts.

(e.g. costs, schedules, testing), subcontracting, carrying out the construction and commissioning the building. The detailed planning included additional activities not needed in a conventional renovation project, for instance, the procurement of subcontractors under the partnering collaboration and searching for technical solutions for the passive house concept. The timeline of the implementation phase of the entire renovation project is 2008 – 2014; the timeline of the demonstration project (18 demonstration apartments in two staircases of a three-storey-building) was one year. The operation phase includes operation and maintenance routines of passive houses and monitoring and verifying the implementation of the passive house concept. Monitoring and follow-up are additional activities related to passive house-oriented renovation on top of conventional renovation processes and thus costs arising in this phase are additional costs of the project. In Brogården, monitoring has been split among many actors and being a development project, it is often financed by R&D. For instance, technical requirements such as thermal comfort, ventilation and indoor environment are verified with measurements after each renovation stage. In addition, the indoor environment is checked through tenant questionnaires.

The total cost of the renovation, including investment, maintenance and rent shortfall is approximately SEK 380 million. On average, the total cost of renovation is SEK 1.28 million per apartment, out of which SEK 0.36 million (28%) is for energy improvements⁸, 0.6 million (47%) for extension and accessibility, 0.24 million (19%) for maintenance, and 0.08 million (6%) for rent shortfall. These cost items do not include transaction costs identified in this study.

Due to the passive house nature of the project, the renovation is carried by partnering, whereby the building owner, the building developer and some subcontractors closely collaborate during the renovation process. Partnering, as described by the literature and re-enforced by the interviewees, is characterized by a common long-term and holistic perspective of participating actors, a framework contract⁹, open books (open cost accounting) and continuous feed-back in terms of evaluation and improvements (Kadefors, 2011).

Alingsåshem (*the building owner*), a municipally-owned housing company administers around 3 000 apartments in the municipality of Alingsås. Alingsåshem has extensive experience in renovations and a management committed to sustainability issues. Skanska Housing (*the building developer*), one of the largest construction companies in Sweden, was procured through tendering for the Brogården project. Skanska has substantial experience in building renovation and supports the passive house concept at top management levels. Out of eight *subcontractors* in the Brogården project, Alingsåshem and Skanska signed five-year partnering collaborations with four: Alingsås Rör (piping), Elteknik (electricity), Bravida (ventilation) and Sandå måleri (painting). In addition, *consultants* were contracted for architecture (efem, Hans Eek, Kerstin Nilsson), structural engineering (WSP), electricity (Picon), heating and ventilation systems (Andersson och Hultmark), monitoring and evaluation (Lund University, SP, Chalmers University). It was recognized early on that *tenant* involvement is essential to further improve the renovation process.

⁸ It is around EUR 154 000 for the total renovation cost and approximately EUR 43 000 for the energy improvements. 1 SEK=0.12056 EUR (www.oanda.com, 14 March 2013)

⁹ As an example of a long-term incentive, the framework contract, apart from the Brogården project, includes additional potential future construction projects.

3 Transaction Costs of Brogården Passive House Renovation

Transaction costs of passive house renovation have been assessed through the case study of Brogården, Alingsås. The assessment includes the identification and categorization of the different sources of transaction costs. In comparison to conventional renovation projects, passive house renovations face higher investment costs and higher and additional transaction costs. These occur in all three phases of the renovation process (planning, implementation and operation) and at different actors' stakes. In addition, the study shows that the scale of transaction costs varies greatly among renovation phases, among categories and among which actor the transaction costs are attributed to.

3.1 The nature of transaction costs

The identified transaction costs of any renovation, including passive house renovations, fall into three categories: due diligence, negotiation and monitoring. All were found in all phases of the life-cycle of the building project, including i) planning, ii) implementation, and iii) operation and follow-up, see Table 1. In this study, due diligence costs include the search for and the assessment of information on, for instance, the form of collaboration, partners, technically and economically feasible passive house solutions, and assessment methods. Negotiation costs arise in the procurement process, during preparation for procurement, contracting, assessment and approval. Monitoring costs include the follow-up on installed technologies, energy use and savings as well as related costs.

In comparison to conventional renovation projects, the transaction costs identified are higher due to the application of the passive house concept. In this paper, the transaction costs are attributed to the actors involved; this study focuses on the building owner and the building developer because most of the cost reduction is assumed to be achieved by these two actors.

Table 1 Conceptual categorization of the nature of transaction costs – based on Brogården passive house-oriented renovation

Nature of TCs/ Renovation phases	Due diligence	Negotiation	Monitoring and verification
Planning	Extended pre-study Procurement of building developer: - search for the form of collaboration - preparation of the call - assessment of applications	Project formulation Target setting	
		Procurement of building developer: - preparation for the call	
Implementation	Search for passive house technology solutions*		
	Procurement of subcontractors: - assessment of subcontractors*	Procurement of subcontractors: - contracting*	
Operation & follow-up	Search for methods and practices of assessment and monitoring*	Contracting evaluators*	Monitoring (equipment, energy savings, costs)
	Assessment of methods and practices of assessment and monitoring*		Maintenance

* Transaction costs in addition to transaction costs of conventional renovations. The other transaction costs are present in conventional renovations, but are lower.

3.1.1 Due diligence¹⁰

Transaction costs of due diligence, specific to passive houses and additional to conventional renovations, occur in all three phases of the renovation project. In the planning phase, transaction costs were identified in relation to the extended pre-study and the tendering procedure for the building developer, i.e. search for the form of collaboration, and preparing and assessing the applications. These transaction costs were borne by the building owner. In the implementation phase, transaction costs were identified in connection with searching for passive house technology solutions and the tendering procedure for the subcontractors, i.e. assessment and approval of subcontractors. These transaction costs are borne by both the building developer and the building owner. In the operation and follow-up phase, transaction costs were identified in relation to searching for and assessing methods and practices of monitoring and evaluation. These transaction costs are attributed to various actors involved in the monitoring process. The scale of transaction costs related to due diligence is estimated to be between 10% and 200% more than for conventional renovations.

Extended pre-study. Renovation processes often include pre-studies consisting of building status investigations and drawings to guide the implementation of the construction, but rarely concrete technical solutions as in the Brogården project. In Brogården, the investigation of the building itself was more extensive than it is in a conventional project; it included the status of insulation, airtightness of the building envelope, moisture content of building materials and indoor acoustics. The investigation was carried out by the SP Technical Research Institute of Sweden where two people worked on it over a one month period (Janson, 2010). The pre-study was carried out by efem Architect Agency and took one full-time person-year, which is estimated to be 50% more (in monetary terms roughly 300-400 000 SEK more¹¹) compared to a traditional renovation project. Both the extended investigation and in particular the detailed pre-study including technical solutions extended the planning phase and was as an additional cost for Alingsåshem¹².

Search for the form of collaboration. In Brogården, the procurement process took longer, than in a traditional renovation project due to the decision-making process - partly about the form of collaboration and partly on the extent of the contract. Although, the idea of partnering was discussed in the first planning meeting (2005), in order to gain more experience Alingsåshem did an extensive literature review, organized study visits and experience sharing meetings during 2005 and 2006¹³ before the final decision on the form of collaboration. In addition, the framework contract included potential future constructions. The actual time Alingsåshem spent searching for the form of the collaboration is estimated to be roughly two months, while the whole decision-making process stretched over a year.

¹⁰ Due diligence, here, refers to the investigation of information, including the search for and the assessment of the acquired information.

¹¹ It is in the range of EUR 36 000 and 48 000. 1 SEK=0.12056 EUR (www.oanda.com, 14 March 2013)

¹² Alingsåshem applied and got funding from the Swedish Energy Agency, the funding covered “additional costs” in the project for the planning process, detailed design solutions, management of the project during the building process, additional support from experts and monitoring of the renovated building with measurements and experiences from the building process.

¹³ Alingsåshem relied heavily on the experience of the Tuggelite project in Karlstad.

Preparation of the call for a building developer. The preparation of the call took longer than in a conventional renovation process. This was due to the inclusion of the partnering contract assessment, which had been used in the Karlstad renovation project, and drafting the partnering framework contract. In addition, the Building Research Council funded consultants to develop qualities and requirements for passive house renovation, which were then also included in the procurement material. Alingsåshem contracted a consultant for the preparation of the procurement material and the call. The drafting took approximately two months.

Assessment of the building developers' applications. The estimated length of the assessment and approval process is 25 hours (30%) more than in case of a traditional tender evaluation. It is not common practice to require detailed curricula and the applicants' personal views, for instance, on sustainability and aesthetics in the call¹⁴. This process included a couple of meetings and interviews with around thirty professionals. The evaluation was carried out by a group of five people from Alingsåshem.

Assessment and approval of subcontractors. Most building developers have established networks of professionals to work with, thus procuring subcontractors, contracting consultants and getting them approved by the building owner were additional activities specific to this project¹⁵. Alingsåshem was involved in the final selection of the four subcontractors included in the partnering contract; the approval of the applications took approximately three person-hours.

Search for passive house technology solutions. Additional costs related to the application of new technologies are very common. In Brogården, additional transaction costs arose from two main sources: a) the search for energy efficient *products* and b) the search for *new solutions*, such as applying already existing energy efficient products in new context, i.e. in renovation instead of new buildings. These costs are mostly attributed to the building developer.

In terms of *products*, it was time-consuming to find energy efficient doors and roof hatches. Airtightness combined with safety (peep-hole) and accessibility (door-bell)¹⁶ features seemed to be a new combination of parameters for door producers. The required U-value of 0.6 W/m²K was not available on the market; the installed entrance doors have now a U-value of 0.75 W/m²K. Airtight and well-insulated hatches providing access to the roof, were also difficult to find on the market. The search for these products took an estimated two to three week per product for the building developer (together with the respective subcontractors).

In terms of *new solutions*, the slab insulation, the wall construction and the ventilation system required additional resources from the building developer and the building owner. The decision to apply PIR (polyisocyanurate foam) insulation to the foundation led to a new research project aiming to show whether and how PIR can be applied in passive house renovations (Skanska, 2012). In terms of outer wall construction, Skanska developed and tested three models as well as educated craftsmen for special installation of the plastic layer. The development of the outer wall construction was estimated to take 10% more time for Skanska due to the additional requirements

¹⁴ These special requirements made both the assessment time and interview time longer. One interview was estimated to take an hour and a half, out of which roughly half an hour was dedicated to sustainability principles.

¹⁵ See the details of procurement under negotiations.

¹⁶ Peep-holes and door-bells decrease the air-tightness of doors.

of passive construction. Designing the ventilation system was an additional resource input specific to passive house renovations, where the ventilation system replaces the traditional heating system. A central ventilation system was designed based on experience from the demonstration buildings. The development of a new ventilation solution for renovated passive houses was estimated to take two to three times longer than the application of an already designed ventilation solution in newly built passive houses.

Search for methods of assessment and monitoring. Monitoring is not necessarily part of conventional renovations; it is often an additional cost when implementing energy efficient technologies. Brogården is a development project, with many actors involved, and monitoring and transaction costs related to the search for monitoring and assessment methods are split among the actors. Some of the most time demanding searches were finding methods for a) calculating and monitoring project financing (attributed to Alingsåshem), b) monitoring energy use and energy savings (attributed to Alingsås Energi and Lund University) and c) developing the process for quality assurance (attributed to SP). These transaction costs are part of the ongoing development project, so no time estimate has yet been made for them.

3.1.2 Negotiations

Transaction costs of negotiations occur in all three phases of the renovation project. In the planning phase, transaction costs were identified in relation to project formulation and target setting. Both project formulation and target setting was a long and complex process including frequent and lengthy meetings and negotiations leading to a stretched decision-making processes; it is partly due to the application of the passive house concept in renovation. In addition, transaction cost was accounted in the procurement procedure, in relation to the preparation for the main call. In the implementation phase, transaction costs were identified in connection to subcontracting and meetings, related to passive house principles and the partnering contract type. In the operation and follow-up phase, transaction costs were identified in relation to agreement negotiations with monitoring partners. The scale of transaction costs related to negotiations can be as high as 200% more than in conventional renovations.

Project formulation. The project formulation in Brogården, from the introduction to the acceptance of the passive house concept, lasted four years (2001-2005) from the very first meeting between an independent consultant-architect and the managing director of Alingsåshem. These negotiations are also common in conventional renovation projects, except that introducing a new concept and persuading different actors to implement them takes more meetings and more time. Considering the management commitment of Alingsåshem, the total time dedicated to negotiations and decision-making would be greatly underestimated if only meeting hours were reported. The time the development director of the municipality spent on project formulation is, for example, estimated to be around 10% of his working time over the project period, totaling SEK 500 000¹⁷.

Target setting. The major targets of the Brogården renovation were specified early on; they were formulated based on municipal housing policies, earlier experiences and tenants' complaints. Targets in relation to energy efficiency are, for instance, a) enhancing indoor comfort, by

¹⁷ It is approximately EUR 60 000. 1 SEK=0.12056 EUR (www.oanda.com, 14 March 2013)

improving U-values and installing mechanical ventilation (with heat exchangers) with the possibility for the tenants to influence their indoor climate and energy use, b) lower energy use, c) easy-to-use and -maintain technology, and d) active involvement of tenants (in the renovation process and in the user-phase). The renovation targets were set by Alingsåshem. There is no estimate available of resources spent on the complex procedure of target setting.

Preparation for the main call. Preparing for the detailed call took more time for the applicants than in conventional renovation projects. Skanska, the procured building developer, spent approximately three times longer on preparing for this call than on conventional renovation tenders. It was partly due to the fact that this was the first time for Skanska to participate in a partnering procurement for renovation and partly due to the sustainability principles (including energy efficiency and the passive house concept) on which Alingsåshem had required the detailed views of applicants.

Subcontracting under partnering. Most building developers have established networks of subcontractors, thus (re-)procuring subcontractors and consultants was an additional activity specific to this project. Skanska (re-)procured and contracted four subcontractors for painting, electrical work, plumbing and landscaping for the partnering collaboration under the terms and conditions of the framework contract. The (re-)procurement of subcontractors took an estimated three weeks (120 man hours) for the building developer.

3.1.3 Monitoring

Monitoring is not typically part of conventional renovations and thus represents additional costs in passive house renovations. Transaction costs of monitoring occur in the operation and follow-up phases of the renovation project. Among the transaction costs identified in this phase were monitoring of energy saving equipment, energy savings, costs and cost savings as well as maintenance of (new) technologies used in passive houses. Monitoring activities are split among multiple actors. For instance, Alingsåshem¹⁸ is responsible for monitoring the performance of ventilation system and finances, Skanska for the moisture content, Alingsås Energi for the energy demand for space heating, domestic hot water, and electricity, Lund University for energy, airtightness and tenants' satisfaction, SP for the monitoring process and quality assurance, and the Tenants' Association for the needs and preferences of the tenants. As the renovation is still on-going, the available results are partial and often related to certain stages of the renovation and not the entire process. The current monitoring costs are estimated to be very high in Brogården¹⁹. Monitoring is expected to be required by legislation in the future, thus monitoring-related costs will no longer be additional transaction costs of passive house renovations.

¹⁸ For instance, it was found that the lack of specification on the monitoring requirements made it difficult for the building owner to follow-up additional costs of energy efficient and passive house technologies per building and/or per apartment.

¹⁹ The quantification of monitoring costs was not the focus of this study; it is however strongly recommended to estimate monitoring costs (with special attention to maintenance costs) once the project is completed.

3.2 Estimated scale of transaction costs

The results of this study indicate that the scale of transaction costs related to the implementation of passive house renovation is non-negligible and can be 200% higher than for conventional renovations (see Table 1). Although it has been difficult to find comparable data on the scale of different nature of transactions costs, this study indicates the importance of considering these costs. This also indicates a need to find ways to reduce them (see Section 4).

In general, project formulation and target setting have shown to be too complex to reliably estimate resources allocated to them. On the contrary, for the extended pre-study, activities related to procurement processes and the search for passive house technology solutions, estimated costs are available - at least in terms of time spent on the activities. The majority of transaction costs arising in the planning phase are naturally attributable to the building owner while transaction costs arising in the implementation phase are mostly borne by the building developer and transaction costs of the operation and follow-up phase are shared among various actors.

Table 2 Estimated transaction costs of the demonstration stage of Brogården renovation (source, scale, attribution)

Renovation phase	Source of TCs	Scale of TCs	Actor bearing TCs
Planning	extended pre-study: - building investigation (consultant) - architecture work (consultant)	App. 2 person-months work 300 000-400 000 SEK ²⁰ (<i>1.5 times more in comparison with a conventional renovation</i>)	Building owner
	project formulation: - (Alingsås hem) - (municipality)	n/a 500 000 SEK ²¹	Building owner
	target setting	n/a	Building owner
	search for the form of collaboration	App. 2 person-months work	Building owner
	call preparation : - call drafting (consultant) - application (Skanska)	App. 2 person-months work (<i>3 times more spent in comparison with a conventional renovation</i>)	Building owner Building developer
	application assessment	(<i>1.33 more spent compared to a conventional renovation</i>)	Building owner
Implementation	subcontracting (Skanska)	App. 3 person-weeks	Building developer
	assessment of subcontractors (Alingsås hem)	App. 3 person-hours	Building owner
	search for passive house technology solutions (Skanska): - products (subcontractors) - new solutions (consultants), e.g. - ventilation - wall construction	App. 2-3 person-weeks per product (<i>For ventilation 2-3 times longer and for wall construction 1.1 times longer than in a conventional renovation</i>)	Building developer
	search for methods of assessment and monitoring (e.g. Alingsås hem, Alingsås Energi, Lund University, SP)	n/a	Building owner
Operation and follow-up	monitoring and assessment (idem)	n/a	Building owner and contracted partners
	maintenance	n/a	Building owner

²⁰ It is in the range of EUR 36 000 and 48 000. 1 SEK=0.12056 EUR (www.oanda.com, 14 March 2013)

²¹ It is approximately EUR 60 000. 1 SEK=0.12056 EUR (www.oanda.com, 14 March 2013)

The type of collaboration has an influence on the nature and scale of transaction costs in passive house renovations. Partnering form was chosen for the collaboration because of the application of the passive house concept. Therefore, some activities related to partnering have been considered as transaction costs of implementing the passive house concept as these costs would not have occurred for other types of collaboration. These costs arise throughout all the three phases of the renovation process and in all natures of transaction costs. For example, it occurs in the form of due diligence, such as call preparation and assessment of applicants, in the form of negotiations, such as project formulation and target setting and in the form of monitoring. In general, most of the actors state that partnering is time-demanding. Skanska, for instance, estimates that the Brogården project, due to partnering and being a development project, requires half a position more (project management hours) than a traditional renovation project. Other activities related to partnering, however, were encountered here as strategic measures for learning (see Section 4.)

4 Strategic measures for knowledge development and learning

As revealed in the previous section, the passive house renovation project, in comparison to conventional renovation projects, required additional resource inputs and/or measures in the different project phases. These measures were often encountered as resource inputs and costs, which by facilitating knowledge development and learning, intend to lead to resource and cost reductions. The study at hand found that the renovation of Brogården included such measures to reduce construction costs and, surprisingly transaction costs as such. These strategic measures are elaborated below.

4.1 Study visits and demonstration projects

Introducing the passive house concept for renovation, in comparison to conventional renovation projects, increases the need for advanced information and knowledge intake. For this reason, in the Brogården project, study visits were organized in the planning and the implementation phases. In the planning phase, the focus of the study visits was on the type of collaboration and the nature of the passive house concept. The partnering contract, for instance, was based on a previously developed partnering contract in Karlstad. These study visits were initiated by Alingsåshem. In the implementation phase, in order to strengthen the common understanding, the study visits concentrated on passive house technologies and addressed different groups of professionals. These visits were organized by Alingsåshem and Skanska – together and/or separately. They took an estimated 72 person-hours from Alingsåshem and Skanska. In the operation and follow-up phase, a demonstration (or showcase) apartment was set up to serve as a subject of a continuous dialogue between tenants and Alingsåshem. In addition, it functioned as a stakeholder meeting point - for example, for site visits and for project and tenant meetings. The showcase apartment, in addition to open house weekends, had regular opening hours. The demonstration apartment was a common project of Alingsåshem and the Tenants' Association on which each actor spent roughly estimated 220 man hours.

4.2 New forms of meetings

A renovation process traditionally requires meetings during all phases: in the implementation phase, the focus includes building planning, building process, time-scheduling and financing; in the operation and follow-up phase meetings address topics like user practices. Introducing the

passive house concept for renovation slightly changes the frequency and objectives of these meetings. Additionally, the type of collaboration (partnering) has also brought about new forms of interaction.

In the implementation phase, *traditional building site meetings*, building planning and building process meetings play an important role in finding technical and economic solutions for the implementation of the passive house concept. In Brogården, Skanska organized these meetings on a weekly basis; the participants often got homework to be solved for the next meeting. To find solutions for problems took on average two to three weeks. According to participating actors, energy efficiency issues occupied between 10-50% of the meeting time²². Among meetings organized in the spirit of the partnering framework contract²³, *start-up partnering meetings* and *Friday meetings*²⁴ are the most important to highlight. Start-up meetings have been organized at each stage of the renovation process: the first meeting took a whole day, the second, a half day, the third, three hours, the fourth and the fifth two hours each²⁵. These meetings also accommodate different guest lectures on topics such as energy efficiency and passive principles. On average, energy efficiency took up 25% of the meeting.

In the operation and follow-up phase, *individual move-in briefings*, regular *information meetings* and topical seminars were organized for tenants. At the individual move-in briefings, in comparison to traditional renovation, additional costs occurred in relation to providing information on passive house principles and practicalities as well as individual carpenter assistance to avoid problems like perforating the air tight layer. Alingsåshem spent an estimated 750 person-hours on the move-in assistance; this resource input would not have been necessary for a conventional renovation. Information meetings and topical seminars include a one-time public start-up meeting (April 2007), a scenario building workshop, and regular meetings often combined with topical seminars and guest lecturers (weekly, later monthly). These meetings were important in order to use the passive house system more efficiently, a concern not present in conventional renovation projects. Alingsåshem dedicated approximately 75 person-hours and the Tenants' Association roughly 50 person-hours to these meetings.

4.3 New information channels: experience database and newsletter

Unlike conventional renovations, passive house renovations require new forms of written information channels, structures and storage; the *experience database* and the *Brogården newsletter*²⁶ are two good examples of these. In the operation and follow-up phase, Skanska set

²² For example, finding solution for the building envelop was estimated to take 10-15%, while finding ventilation system solutions was estimated to take 50% of the meeting time. On an average, 92 person-hours were estimated to have been spent discussing energy efficiency issues in the frame of building planning and process meetings.

²³ Partnering is based on the principle that involved project partners work with a defined target and a common goal in mind; it thus requires meetings, active participation (direct ideas and solutions from the entrepreneurs), close collaboration between the different professions and teambuilding.

²⁴ Friday meetings take place every fifth Friday. So far approximately 45 meetings have taken place (February 2008 - January 2013).

²⁵ The first start-up meeting took place before the renovation started; all involved project participants (43 participants) attended a one-day meeting in Alingsås. The aim of this session was to present the vision, the goals and the targets of the renovation project. The passive house concept was delineated among actors by presentations (a 3.5 hours energy presentation, focusing on ventilation and outer walls) and team-games (a quiz competition).

²⁶ The newsletter is available at <http://www.alingsashem.se/index.php?page=bobladet>

up a database with experience gathered from various partners involved in the renovation (i.e. performance evaluation). Experiences range from technical details through working process-oriented issues to new ideas for the future. The aim is to ensure continuity and to improve the (stages of the) renovation processes in the future. Another example of new information channels is the end-user involvement in the appropriate application of new technologies, which was also recognized early on in the Brogården project. The newsletter *Brogårdsbladet* has been one of the most important information tools for tenants to get acquainted with the details of the renovation process, passive house principles and measures. It has been issued and distributed to each apartment on an average 1.5 times per month since 2007. The newsletter is a common responsibility of Alingsåshem and the Tenants' Association and takes one person-day per month for Alingsåshem (456 hours), 50% of the working time of one worker at the Tenants' Association and one person-day per issue for Skanska (224 hours).

4.4 Potential for transaction cost reductions

The strategies and measures discussed above have provided a potential for knowledge development and learning in passive-house renovations. This, in turn has reduced construction and transaction costs. One indication of this is that the actual construction time was reduced from 12 months, as of the first renovation stage (demonstration project), to 7.5-10 months for the later renovation stages. The various strategic measures applied had an effect on the different sources of transaction costs.

Transaction costs of due diligence and the search for passive house technology solutions were reduced by study visits, demonstration projects, new forms of meetings and new forms of documentation. The searches for the form of collaboration and for assessment and monitoring methods were reduced by study visits, demonstration projects and new forms of meetings. Transaction costs of negotiations, such as project formulation and target setting were reduced by study visits, demonstration projects, new forms of meetings and new forms of documentation. Preparation for the main call can be reduced by new forms of meetings (see more details in Table 2). In addition, different ways to provide information provision to tenants (for example, the demonstration apartment, new forms of meetings and newsletters) seemed to contribute reducing transaction cost in relation with the operation and maintenance of passive house technology solutions. Monitoring activities also serve as a basis for learning from own experience and thus contributed to cost reductions in all phases of passive house renovation.

However, not all transaction costs could be reduced through learning. This study shows that transaction costs of due diligence, such as extended pre-study and the assessment of building developers and subcontractors have little room for reduction through learning. Similarly, transaction costs of negotiations, such as subcontracting and monitoring show very low or no reduction potential. This is because feasibility studies, building investigations and technical procurement requirements are highly building specific.

Table 3 Strategies for learning to reduce construction costs and specifically transaction costs in Brogården

Strategies promoting learning:		Study visits & Demonstration projects	New forms of meetings	New channels of information
Transaction costs:				
Due diligence	Extended pre-study			
	Search for form of collaboration	√	√	
	Preparation of the call for building developer	√		
	Assessment of building developers' application			
	Assessment of subcontractors			
	Search for passive house technologies	√	√	√
	Search for assessment methods	√	√	
Negotiation	Project formulation	√	√	√
	Target setting	√	√	√
	Preparation for the main call		√	
	Subcontracting under partnering			
Monitoring	Monitoring			

5 Concluding remarks

To overcome barriers to energy efficient renovations and to make passive house renovations more attractive, transaction costs related to the introduction and implementation of passive house technologies must be better understood and ultimately reduced. This study has identified three natures of transaction costs arising during the application of the passive house concept: due diligence, negotiations and monitoring. Due diligence costs arise in relation to extended pre-study, search for the form of collaboration, passive house technology solutions and monitoring methods, preparation of the call for building developers, and assessment of the applications of building developers and subcontractors. Negotiation costs occur in relation to project formulation, target setting, preparation for the call for building developers and subcontracting under partnering. Transaction costs of monitoring arose in relation to monitoring of energy and cost savings, energy efficient equipment and maintenance of passive house technologies. It was found that certain natures of transaction costs, for example due diligence and negotiation, can arise throughout the life-cycle of the passive house renovation project; while monitoring is more typical in the operation phase. The results also indicate that the transaction costs of passive house renovations are higher than transaction costs of conventional renovations. Out of these, most of the costs occur in the planning and implementation phases. Most of the costs arising in the planning phase are borne by the building owner, while costs arising in the implementation phase are typically borne by the building developer. It is assumed that a high proportion of these costs can be reduced through learning. It was found that certain strategies have already been introduced and applied to varying extents in the Brogården project to promote learning and cost reduction. These are actors' strategies such as study visits, demonstration projects, new forms of meetings and written information to open up new information channels. These strategies have been applied, for instance, to reduce additional costs related to project formulation, target setting and the search for passive house technologies, which seems to be the highest transaction costs in the Brogården project. This is surprising, considering that even if stakeholders are sometimes fully aware of the existence of transaction costs, they do not keep track of them and/or implement strategies to reduce them.

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