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Final Report

The Dynamics of Building Technology Development in Switzerland

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EXECUTIVE SUMMARY

The report at hand sheds light on the dynamics of building technology development in Switzerland. It aims at providing an understanding of the diffusion dynamics for energy efficient technologies, and on the role of policy intervention in particular. Thereby, mechanisms that lead to an efficient acceleration in the market diffusion of energy efficient building technologies are to be detected.

To do so, we examine the historical developments in the diffusion of three selected technologies, heat pump, low-e glazing, and comfort ventilation technology, and distill our findings into an overarching framework. To retrace the developments retrospectively, we collected archival data, conducted expert interviews, and then analyzed both of them.

We find that the maturity of an innovation's technological system along with its diffusion status determines the effectiveness of policy instruments. We show that with a weakly developed system, policy needs to first foster mainly industry-specifically (e.g. via R&D grants, conferences/fairs, P&D projects) to enable the industry to manufacture the technology at a quality and reliability level that allows to compete against default technologies. Once the system reaches a reasonable maturity level (juvenile), other market dynamics, such as labels, are efficient measures to stimulate demand by creating legitimacy, thereby benefiting from the higher demand of the label as a whole. A very mature system allows to apply performance standards (e.g., u-value limits) and gradually adapt them over time.

This report contributes to different bodies of literature (diffusion theory, environmental policy, technological evolution) but first and foremost, it should provide guidance to decision makers from business and policy in understanding the diffusion dynamics and their intertwining with policy intervention. In doing so, it promotes the pursuit of a more energy efficient and decarbonized society.

1 Introduction

This section introduces the topic of the report, the dynamics of building technology development in Switzerland. First, the motivation for our research is outlined. Then, we touch upon the state of knowledge by reviewing the related literature and discussing

1.1 Motivation

To mitigate climate change, energy efficient technologies (or low-carbon technologies) play an essential role in the decarbonization of society. As this is widely conceived, academic research, avid entrepreneurs, and national governments have invested huge efforts to study, market, and foster energy efficient technologies. Consequently, already today there is an abundance of energy efficient technologies commercially available that are economically and ecologically superior to their 'high-carbon' competitors. However, as the mechanisms of the free market seem to be not strong enough, these low-carbon technologies often fail to diffuse and become predominant, thus missing out on large potential.

To reap this potential, in various industries (e.g., energy, transportation) we have seen a relatively long history of heavy policy intervention drawing from a broad landscape of instruments to accelerate implementation and market diffusion of low-carbon technologies. Or as the OECD [1] states:

> *"There is no guarantee that innovations will appear when and where they are most needed, or at a price that reflects all environmental and social externalities associated with their deployment. Governments need to create a policy environment that provides the right signals to innovators and users of technology processes, both domestically and internationally […]."*

Therefore, this study addresses the following research question: how can policy instruments efficiently accelerate the implementation and diffusion? We aim at exploring the relation of policy instruments fostering the diffusion of low-carbon innovations and the influence of technological characteristics.

The relation of policy measures triggering the implementation and diffusion of energy efficient innovations is a topic that has been investigated in multiple ways in literature. Some scholars assess a specific policy instrument, others study a specific technology, while still others analyze the quantitative relation between policy and diffusion, thus not exploring mechanisms in detail.

The multitude of policy measures can be differentiated into technology-specific ones (those that directly or indirectly support a particular technology) or less specific ones (targeting emissions). While from a mainstream economic perspective the latter might be superior in terms of efficiency (introduction of pigouvian tax to internalize the external cost of emissions), the former enjoy a much higher degree of public acceptance still at a fair level of efficiency. This is why we focus on technology-specific policy measures, both direct and indirect ones, (such as subsidies, standards, labels) to find out how to choose from the broad spectrum of measures and deploy selected ones in an efficient manner to accelerate the diffusion of a low-carbon innovation.

We draw from selected technology case studies and explore their historical diffusion over time along with the deployed policy instruments. To do so, we reviewed the existing literature, analyzed archival data, and conducted expert interviews in order to grasp the mechanisms in the diffusion dynamics for each case. Finally, we propose a framework that provides guidance for policy and decision makers in efficiently supporting the acceleration of the diffusion of low-carbon innovations.

1.2 State of knowledge / Literature review

The following subsections shed light on the existing literature that is related to our field of research. We first start by reviewing diffusion theory in brief (subsection 1.2.1), then add the policy perspective to the diffusion (subsection 1.2.2), and finally complement it with literature that takes technological characteristics into account (subsection 1.2.3).

1.2.1 Diffusion

Originating from a study on the diffusion of hybrid corn [2], research on the diffusion of innovation has gained popularity and has been shaped to a large extent by two scholars: Everett Rogers and Frank Bass. In 1962, Rogers published his first edition of “Diffusion of Innovations” [3] where he characterizes the diffusion process with its different stages and types of adopters and introduces the concept of S-shaped diffusion curves (for cumulative adoption), as shown in Figure 1 below. Bass developed 1969 a mathematical model to describe the product adoption following the prior described s-curve concept [4].

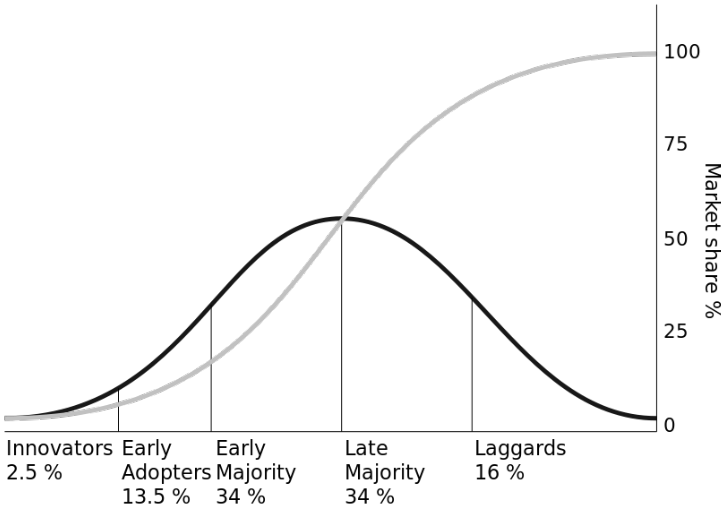


Figure 1: Diffusion process according to Rogers [5]

According to Rogers [5], diffusion is *“a process in which an innovation is communicated through certain channels over time among members of a social system”.* These members adopt the technology at different points in time, thus can be characterized according their willingness to adopt into the following groups: innovators, early adopters, early majority, late majority and laggards. These adopter groups can be defined by the specific market shares for each group. Other scholars, such as Grübler et al. [6], have empirically analyzed the diffusion curves for different technologies (e.g., steel production, transportation) in detail and retrospect.

Besides the large variety of studies, the focus of this report lies on Rogers’ work as it represents the most prominent contribution in the diffusion theory. To review the existing research field, Peres et al. [7] published a most recent overview on selected literature on innovation diffusion.

1.2.2 Diffusion and Policy

There are various studies on the effects of policy measures on the diffusion of energy efficient technologies. Gillingham and Sweeney [8] investigate major barriers for the diffusion of low-carbon technologies in general, whereas Ürge-Vorsatz et al. [9] provide a comprehensive overview of different policy instruments and their cost-effectiveness specifically in the building sector.

Table 1 gives an overview on reviewed publications in the field of policy design concerning the diffusion of technologies.

Table 1: Selected publications on policy effects on the diffusion of technology

Author/s	**Scope**	**Findings**
Foxon et al. (2005) [10]	Analysis of the British new and renewable energy technologies innovation system and formulation of policy recommendations	• Policy framework should be stable and consistent • Policy design should aim at aiding demonstration and pre-commercial stage by improving risk/reward ratio

Koski (2007) [11]	Creation of typology for characterizing the structure of policy design on the basis of the case of concentrated animal feeding operation regulation	• Identification of three dimensions of policy designs: scope, stringency and prescription
Nill and Kemp (2009) [12]	Assessment of 3 evolutionary policy approaches (strategic niche management, transition management, time strategies) about policy effectiveness for radical and systemic transition.	• Integrated evolutionary approach favors a radical technology change • Barriers for innovation overcome by studying technology innovation systems
Gillingham and Sweeney (2009) [8]	Review of major barriers to adoption for low-carbon technologies according to four technology categories as well as assessing potential policy strategies	• High cost and institutional failures as barrier for energy-efficient technologies • Technology specific policy recommendation
Grösser et al. (2006) [13]	Generation of preliminary system dynamics model for the system of residential building environment and assessment of possible policies	• Demand side as bottleneck for diffusion process • Most effective effects are: word-of-mouth effect, market pull effect and market saturation effect
Ürge-Vorsatz et al. (2007) [9]	Assessment of 20 policy instruments in the building sector in order to evaluate their potentials to effectively reduce barriers for CO^2 emission reduction measures.	• Effective policies: Appliance standards, building codes, tax exemptions and voluntary labelling • Cost-effective policies: Appliance standards, demand-side management programs, mandatory labelling • Optimal policy design dependent on location, economy and culture

In addition to the specific publications above, there are other important strands of literature truly worth to mention and we briefly describe their focus below.

A technological innovation system (TIS) can be defined as “a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology.” [14]. It comprises components (so called ‘structures’) and observes their dynamics over time (e.g. via seven ‘system functions’). The TIS concept is popularly used to investigate socio-technical transitions (i.e., transitions from one regime to another), thus capturing the development, diffusion, and usage of an innovation within its system. Thus, the TIS focus lies on the system perspective in general and not in detail on specific technological aspects, policy instruments, or diffusion dynamics.

Similar to the TIS concept, the multi-level perspective (MLP) can be applied to analyze socio-technical transitions. The MLP considers transitions as non-linear processes on three analytical levels: niches, socio-technical regimes, and an exogenous socio-technical landscape [15]. Innovations are developed at the niche level and can evolve to the regime level, when sufficient pressure at the landscape level destabilizes the existing regime. As with the TIS concept, the MLP brings the system as such and its transition into focus and does not cover technologies or policies in particular.

Strategic niche management promotes the “development and use of promising technologies by means of experimentation, with the aim of (1) learning about the desirability of the new technology and (2) enhancing the further development and the rate of application of the new technology” [16]. Thus, it aims at strategically creating protected spaces for innovations or their specific applications and emphasizes the aspect of learning. In doing so, the focus of strategic niche management is on the development and on a very early diffusion phase (Rogers’ early market phase), hence it captures the diffusion only in part.

Inspired by the academic subfield of biology, evolutionary economics views economy in a continuous, dynamic process that requires ongoing transformation by individuals, organizations, and society as a whole. It “offers clear insights into the mechanisms that underlie innovations, structural changes and system transitions […]” [17]. Prominent scholars of evolutionary economics, such as Schumpeter, Dosi, Nelson & Winter, set landmarks with their work on the broad concepts of innovation, technical change, and technology policy. However, evolutionary economics falls short in empirically investigating the specific diffusion dynamics and their relation to particular policy instruments.

1.2.3 Diffusion, Policy, and Technological Characteristics

Technological characteristics of innovations have been examined in the context of diffusion, for example by Rogers [5] who identified five key characteristics (relative advantage, compatibility with user habits, complexity of use, trialability and observability), mainly from the perspective of the adopter.

Innovations are commonly classified as being of incremental or radical nature. Murmann and Frenken [18] distinguish two dimensions that define this nature of an innovation: antecedent (i.e., the degree of new knowledge necessary for the innovation) and consequence (i.e., the performance increase caused by the innovation). Thus, a radical innovation is characterized by a high performance improvement and/or large amounts of new knowledge.

In the context of technical change and evolutionary economics, a more production oriented description is given by Davies [19] who distinguishes between complexity of product architecture, scale of production process, market structure and degree of governmental involvement.

Fichter and Clausen [20] bring the three perspectives together by identifying six influencing factors of diffusion, covering technological characteristics (according to Rogers) and political factors being among these six. Additional factors are adopter/end-user factors, supplier factors, sector related factors, and path dependent factors. By empirically analyzing 100 greentech innovations, they find a typology of five diffusion pathways.

2 Methodology

This section outlines our methodological approach for the study. We start by describing the case selection and the sampling strategy, and then, present how we collected and analyzed data via both, interviews and archival data.

2.1 Case selection & sampling strategy

From the multitude of low-carbon innovations we draw technologies that are already diffused to an adequate level in the market (market share >50%) due to the retrospective analysis. Successfully diffused technologies give valuable insights into the mechanisms between deployed policy measures and diffusion, even though the so-called pro-innovation bias misses out on stories of failure where diffusion did not kick in (yet) despite heavy policy efforts. However, we consider that the benefits of focusing on successfully established technologies outweigh aspects of disregarding counterfactuals which seems to be in line with contemporary research [21]. Furthermore, we focus on innovations that contribute to a reduction in energy use (or an increase in energy efficiency) and whose development and diffusion are to a notable extent shaped by policy intervention. With the building sector, we identified an area that has ever since been prone to regulatory measures, given its pivotal role as a large contributor to the total global energy demand (viz. one third).

In addition to exhibiting a high diffusion level (cf. market share), it is pivotal for detecting mechanisms of diffusion effects triggered by policy to observe technologies in their lead market, i.e., the geographic area that delineates an innovations appearance, initial spread, and market take-off. This guarantees that the observed technological development is strongly linked to the supporting policy activities within the country. As a fourth criterion, we needed to sample from a heterogeneous set of technologies, thus altering technologies with regards to their characteristics (system and product properties) in order to decode how policy instruments differ with technological characteristics.

We identified and selected three technologies which meet the established criteria, all being energy efficient technologies in the built environment, namely heat pump, low-e glazing, and comfort ventilation.

Even though we acknowledge the advantages which an increased sample size would yield, we argue that by addressing these three technologies it is feasible to create an explorative understanding about diffusion dynamics and distill the main mechanisms. For all of the three technologies, Switzerland was the lead market (or among the initial markets) that shaped development and diffusion of the innovation. By now, these technologies either have a significant higher market share in Switzerland than in comparable countries (Austria, Germany), or managed to reach this market share in Switzerland much earlier than in other countries.

Table 2: Sample of technology case studies and criteria

		Technology		
	Criteria	Heat pump	Low-e glazing	Comfort ventilation
	Lead market/s	SUI, SWE	SUI, GER	Scandinavia, GER, SUI
Switzerland	First appearance	1970	1979	1990
	Market share (early)	10% (1992)	10% (1986)	6% (1999)
	Market share (late)	>80% (2008)	80% (1999)	50% (2015)
	Efficiency potential	50-75%[a]	-49%[b]	-70%[c]
Characteristics	Technology (product level)	Radical (performance & knowledge)	Incremental (radical in production process)	Radical (performance)
	Maturity of techn. system (at introduction)	Infantile	Adult	Juvenile

[a] Energy savings compared to conventional gas/oil boiler. Additionally, significant reduction of CO_2 emissions.

[b] Improvement of insulation (heat losses, u-value) compared to a standard insulating glass.

[c] Reduction of ventilation losses in comparison to manual ventilation.

2.2 Data collection: interviews & archival data

The collection of data for our analysis was obtained through the application of two methods: analysis and integration of secondary and archival data as well as semi-structured interviews with different experts. The former was used to map prevailing policies, technology performance data and changes of exogenous influences. The latter helped to create an understanding about the historic development of the technology throughout the diffusion process and at evaluating the influence of individual policy instruments.

From November 2014 to July 2015, we conducted semi-structured expert interviews with 21 experts in total, thereof ten experts designated to the heat pump case, six affiliated to the low-e glazing case, and five experts from the comfort ventilation case. To select experts, we applied a combination of purposive sampling and snowball sampling. That is, firstly we aimed at identifying potential interviewees by an extensive web search for main stakeholders (from industry, academia, and policy). Then, we added further experts through snowballing as they were mentioned multiple times during different interviews. Table 3 shows an overview and categorization of the interview partners along with their most recent position. Interviews were conducted both in person and via telephone according to the preference of the interviewee. Interviews were recorded with a desk microphone and afterwards transcribed using f4 transcription software.

For the analysis, a triangulation of methods was used in order to obtain results from both information sources, archival data and transcribed semi-structured interviews. Transcripts were revised and processed using grounded theory as an inductively based analytical strategy as described by Saunders et al. [22] which is composed of three steps: open coding (disaggregated into isolated units/codes and consequent clustering into categories), axial coding (creation of relationships between code labels and structuring in hierarchical form), and selective coding (categories are reevaluated to identify core categories on higher level of aggregation/ abstraction). As described by Langley [23], we often iterated between the empirical data and different literature strands, as the combination of these two enables a better understanding of the main mechanisms.

Table 3: Overview of expert interviews

#	Category	Position
Heat pump		
1	Manufacturer	General manager of a manufacturer
2	Association	General manager of a planning office
3	Academia	Heating engineer
4	Association	Marketing manager of an association
5	Association	General manager of a planning office
6	Manufacturer	General manager of manufacturer
7	Manufacturer	Technical journalist for heating manufacturers / distributers
8	Association	Product manager
9	Manufacturer	General manager of a manufacturer
10	Manufacturer	Seller for a heat pump distributer
Low-e glazing		
1	Manufacturer	Group Manager/ Communications of a major glass manufacturer
2	Manufacturer	Branch Manager of a major glass manufacturer
3	Academia	Lecturer for building physics at an applied university
4	Association	Board member of a glass association
5	Manufacturer	Branch Manager of a major glass manufacturer
6	Academia	Professor for building technologies
Comfort ventilation		
1	Manufacturer / Association	CEO of energy consultancy / Member of label association
2	Association / Academia	Professor for building technologies / Chief of label association
3	Manufacturer	Leader of energy consultancy
4	Manufacturer	Project Manager at a manufacturer
5	Association	Associate at a professional association

3 Case 1: Heat Pump

This section presents the case of the heat pump technology. First, we give a brief description of the general working principles, before we recapitulate the historical development of the heat pump with a focus on four distinct aspects: diffusion data and process, technology performance, technological system, and policy measures. Then, we explore causalities by discussing drivers of diffusion and the role of policy instruments.

A heat pump is a device that transfers heat from a low temperature source to a high temperature source using thermodynamic principles. There are three main low temperature sources, air-, water- and ground-sources (yet, air- and ground-sourced heat pumps are most common in residential applications). The process of transferring heat from a low to a high temperature source requires a certain amount of electric energy. The working principle behind a heat pump is a specific thermodynamic cycle, the vapor compression cycle, which consists of four elements: compressor, evaporator, condenser and expansion valve. The compressor is the only element which is powered by and uses electric energy. Since the required amount of electric power is lower than the extracted heat, heat pumps count as an energy efficient technology. Compared to their fossil-fueled rival technologies, namely oil or gas boiler, the heat pump technology reduces the required energy by 50 to 75% and additionally limits CO_2 emissions, depending on the carbon intensity of the electricity used. By electrifying the heating of buildings, heat pumps contribute to the mitigation of climate change as electricity allows for an easier decarbonization.

3.1 Retrospective observations

3.1.1 Market and diffusion

Heat pumps were already constructed and installed in the first half of the 20th century. However, an actual market for heat pumps did not develop until the late 1970s. Diffusion data for Switzerland shows that heat pump sales fluctuated between 1970 and the early 1990s and experienced a severe collapse in the late 1980s. The market stabilized and resurged in the mid-1990s and subsequently experienced a phase of rapid growth until 2008. Annual sales rose from 2.260 units in 1992 to 20.670 units in 2008, representing an increase in market share from 10% in 1992 to above 80% in 2008 for newly built one- and two-family houses. After the peak in 2008, annual sales dropped slightly and stabilized at a high level of 19.350 units in 2013, and a plateauing market share at around 80%. Figure 2 shows the market share of heat pumps for new built one- and two-family houses from 1970 to 2014.

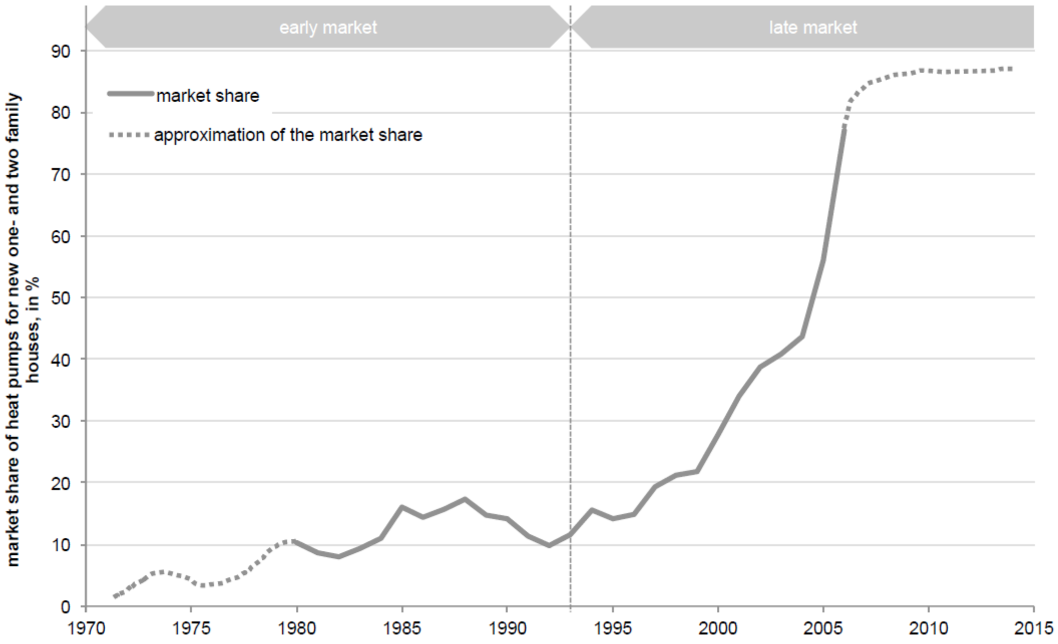
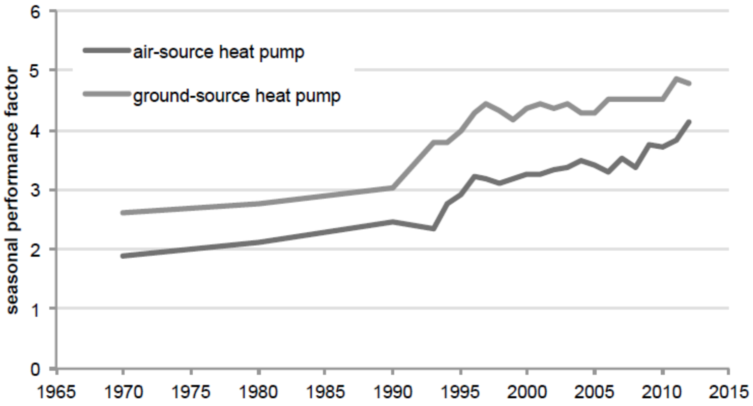


Figure 2: Diffusion of heat pumps in Switzerland (based on [24])

3.1.2 Technology performance

This subsection presents information on the evolution of the heat pump technology from 1970 until 2014. According to the interviewees, three technical indicators were important for the diffusion of heat pumps: the seasonal performance factor[1] (SPF), capital and operating costs, and reliability.

Figure 3 displays the evolution of the SPF which increased significantly from 1990 to 1993. In the early 1990s, heat pumps had higher efficiencies and smaller sizes than heat pumps in the mid-1980s. The continuous performance improvement through development and replacement of components caused the efficiency gains from the early 1990s on.



1970 - 1990: according to an expert survey
1993 - 2009: according to heat pump test-center WPZ

Figure 3: Seasonal Performance Factor (SPF) from 1970 to 2014

High investment costs and insufficient profitability (total costs over lifetime) were reported reasons for heat pumps to not to not fully capture their market potential in an early phase. However, until 1992, capital costs decreased to around 65% of the capital costs in 1980. The continuous reduction of investment cost was mainly resulting from lowering production costs via standardization of components (economies of scale) in 1990s which facilitated the subsequent series production in the late 1990s. Operating and maintenance costs decreased over time due to better control systems, which simplified problem-solving processes.

With regard to reliability, heat pumps in the early phase, until the late 1980s, had several technical teething problems (malfunctioning, noise, life time) which caused bad reputation and, therefore, mistrust by customers. As with the efficiency, from the 1990s on, reliability was reached by continuous improvement and quality measures (e.g., reduction of noise emissions by sound insulation and smoothly operating components). In addition, the performance duration of heat pumps was guaranteed to around 25 years in 2014.

3.1.3 Technological system

A large variety of actor groups were involved in the development, production and diffusion of heat pumps. In addition to end consumers, we can distinguish between actors associated with the production and installation of heat pumps (e.g., manufacturer, architects/planners, installation suppliers), organizations (e.g., R&D organizations), and institutions (e.g., certifying bodies, test institutions, authorities).

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[1] SPF is the average coefficient of performance (COP) over the heating season and is therefore a more relevant performance measure.

During the beginning of the market formation in the 1970s, actors were small and operated locally. From the beginning of the 1970s onwards, more and more firms entered the market avid to profit from the desired gold rush. The use of low cost components and undersized designs led to a lack of reliability in heat pumps which was one reason for malfunctioning HPs and the resulting mistrust towards the technology. Quality oriented firms started to enter the market in the early 1980s and numbers of actors increased. After the market collapsed with falling oil prices in the mid-1980s, numbers of actors dropped dramatically, thus causing a diminishment of the pool of skilled workers in manufacturing, retail and maintenance.

3.1.4 Policy measures

The support for residential heat pumps started in 1979 with the "Eidgenössische Abwärmekommission", the predecessor of BFE's ambient heat department, fostering the technological development of heat pumps for residential buildings. Until 1980s, policy instruments included information and education campaigns in the form of conferences and guidelines to train the workforce. Then, policy activities expanded to the founding of test facilities, at EPFL in 1980, and the planning of pilot and demonstration (P&D) projects in 1981/82 by the national energy research fond (NEFF) and the SFOE. In 1985, the regulatory environment was complemented by an air pollution regulation ("Luftreinhalteverordnung") which limited the emissions by fossil heating devices. The SFOE launched the public leadership program "Energy 2000" in 1990 which, among many other aspects, aimed at fostering the diffusion of heat pumps.

The year 1993 was marked by the foundation of the Swiss heat pump promotion association (FWS) which was as an initiative by "Energy 2000". FWS members represented all relevant actors of the nascent industry/market. FWS fostered coordination as well as education, training and networking activities and was enacted as a "strategic and coordinated program to re-ignite the market" [21]. Other policy measures of the renewed support phase included the foundation of an additional test facility in Winterthur-Töss in 1993 and the first heat pump exhibition in 1996. Furthermore, information campaigns were developed and guidelines for an appropriate dimensioning of heat pumps published.

Form an economic perspective, public financial subsidies were launched, both direct and indirect, in order to support testing and deployment activities like R&D and quality assurance. Total financial support peaked in 1996 with an annual spending of approximately CHF 12 million, subsequently decreased to CHF 6 million 1998, and did not decrease much afterwards. A subsidy for ground-sourced heat pumps was introduced in 2014 where house builders were granted a discount of CHF 3.000. Financial subsidies were considered as "strategic incentive and catalyst". In 1997, a standard was introduced limiting the share of non-renewable energy use for domestic and water heating up to 80% in new buildings. Public standards were first introduced by canton Zurich but quickly diffused to the remaining cantons. In 2000, the SFOE replaced "Energy 2000" by "Swiss Energy". Last major policy instrument was the implementation of a CO_2 levy in 2008 which initially penalized CO_2 production with CHF 12 per ton CO_2. Later, the stringency of this levy increased to CHF 36 per ton CO_2 in 2010 and CHF 60 per ton CO_2 in 2014.

Table 4 lists the main policy instruments and events in chronological order that influenced the diffusion of heat pumps in Switzerland from 1974 to 2014, based on Kiss et al. [21] and expert statements.

Table 4: Overview of major policy instruments and events related to the diffusion of heat pumps in Switzerland

Year(s)	Policy instruments / Events
1974	1st guidelines of the Swiss Association for Refrigeration
1980	1st conference on heat pump technology in Switzerland
1980	1st 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)
1985	Air pollution regulation ("Luftreinhalteverordnung") limiting emissions by fossil heating devices
1990	Launch of Energy2000 (SFOE), public leadership program
1992	Heat pump promotion program (Energy2000)

1993	Foundation of the Swiss heat pump promotion association (FWS)
1993	Additional heat pump testing facility (Winterthur-Töss)
1993-95	Subsidy for heat pumps in existing buildings
1993-96	Handbooks for better heat pump installations
1995	FAWA - heat pump systems, field testing (SFOE)
1996	Peak of financial total subsidies (direct/indirect) with an annual sum of CHF 12 million
1996	1st heat pump exhibition (trade fair for the general public)
1997	Subsidies supported by some electricity utilities
1997	Public standards limiting the use of non-renewable energies for domestic and water heating of new buildings to max. 80% (first in Canton Zurich)
1997	Introduction of “Minergie house” concept as a voluntary standard
1998	Heat pump retrofit program and competition (R&D and subsidies)
1998	Creation of heat pump quality label DACH (Germany, Austria, Switzerland)
2000	Launch of Swiss Energy (follow-up program of Energy 2000)
2001	DACH label for drilling companies
2006	Regular 3 day training program for installers
2008	Implementation of a CO_2 levy in 2008, increasing stringency in 2010 and 2014
2014	Incentive (discount of CHF 3.000) for house builders to install a ground-sourced heat pump

3.2 Illuminating the role of policy instruments

In general, two major functions can be distilled from the historic observations above, each of them were accompanied by different policy instruments. First, reliability and legitimacy, a pivotal issue not only in the early market phase, was strategically addressed with knowledge development (via conferences, R&D grants, trainings and information campaigns), quality control (testing facilities and field testing, guidelines/handbook, DACH label), and networking (via FWS association, trade fairs). The fulfillment of this function to a high degree is a prerequisite for the second function to be effective. Several experts and archival documents stated the significant influence of FWS on the reliability and quality of installed heat pumps, thus by increasing trust and acceptance also strongly pushing the market diffusion (“Since the foundation of the FWS, the heat pump spread rapidly”). The second function, marketability, thus could only be tackled effectively once initial teething problems such as malfunctioning or inadequate dimensioning were removed and the heat pump technology reached a satisfying level of technical maturity and reliability. Marketability was approached by funding and promotion measures (via financial invectives, subsidies, Minergie label) and regulatory standards (via 20% RES share, energy efficiency standard).

4 Case 2: Low-e Glazing

In this section, we describe the case of the low-e glazing technology. As in the previous case, we first give a brief description of the general working principles, the retrospectively analyze diffusion data and process, technology performance, technological system, and policy measures. Finally, we conclude by shedding light on causalities, that is drivers of diffusion and the role of policy instruments.

The low-e glazing technology indicates that low emissivity (thus ‘low-e’) coated float glass was used for the manufacturing of a given window. The term low-e coating describes a layer of a specific metal which is coated onto one or more sheets of regular float glass. The characteristic property of this specific coating is a reduced emissivity which ultimately reduces the heat transfer coefficient, the u-value, an indicator to quantify heat losses through a given object, given in W/m^2K. Due to its main purpose, the reduction of heat loss, low-e glazing is usually deployed in buildings in which heat loss through windows is especially critical for example in residential buildings. The common term for this type of glass is insulating glass or insulated glazing. Initially, a typical insulating glass consists out of three elements: float glass wrapped with one-sided low-e coating, a gas filled interspace, and a spacer. This type of glass is designated as ‘two times insulating glass’ which we refer to as 2-IG. Nowadays, ‘three times insulating glass’ (3-IG) is the established glass standard in Switzerland. This term refers to a glass design with two gas filled interspaces and two low-e coatings. The low-e glazing technology improves the insulation of the building envelope by around 50% (reduction in u-value from a standard insulating glass to a 2-IG low-e glass) but it also allows lower solar heat gain coefficients, thus reducing cooling efforts in summer by less solar transmittance [25]. Therefore, low-e glazing is considered an energy efficient innovation that contributes largely to a reduction in energy demand in the built environment, especially as it targets, new-built, retrofit, and renovation likewise.

4.1 Retrospective observations

4.1.1 Market and diffusion

In 1973, first glass manufacturers in Switzerland attempted to innovate their current product portfolios and single companies started to offer first 2-IG products in 1973. Other companies started to integrate low-e coated glass to their portfolio between the end of the 1970s and the beginning of the 1980s. From 1985, the market started to take off accompanied by a fast growth rate. Between 1985 and 1990, the market share for low-e glass (2-IG) grew from zero to 60% with an absolute annual increase of approximately 12%. According to Rogers’ definition a mass market was already reached in 1987 which complies with many interview statements. After the initial growth phase between 1985 and 1990, growth slowed down and market share for 2-IG peaked in 2001 at around 80%. In 1998, low-e coated glass (2-IG) was “recognized as a commodity”, according to one of our experts. Subsequently, growth rates declined slowly until 2006 and then quickly dropped simultaneously to the smooth transition towards low-e’s next generation, the 3-IG.

Similar to 2-IG, low-e 3-IG products were already available in 1980 before the actual market started to spread from the early 2000s. According to our interviewees, the mass market for 3-IG was reached between 2003 and 2004 when big glass manufacturers started to switch their production line to 3-IG, with particular companies achieving 3-IG production capacities of 50% in 2005. Market share rapidly increased from 2007 onwards and peaked in 2009/2010 with an annual doubling of market shares. An estimation of today’s market share of 3-IG in Switzerland is based on the documented production capacities of two major glass manufacturers. Expert estimations vary between 80% and 90%.

Figure 4 shows the market share of low-e glass, both 2-IG and 3-IG, from 1985 to 2015 based on Jakob [26] and input data from the expert interviews.

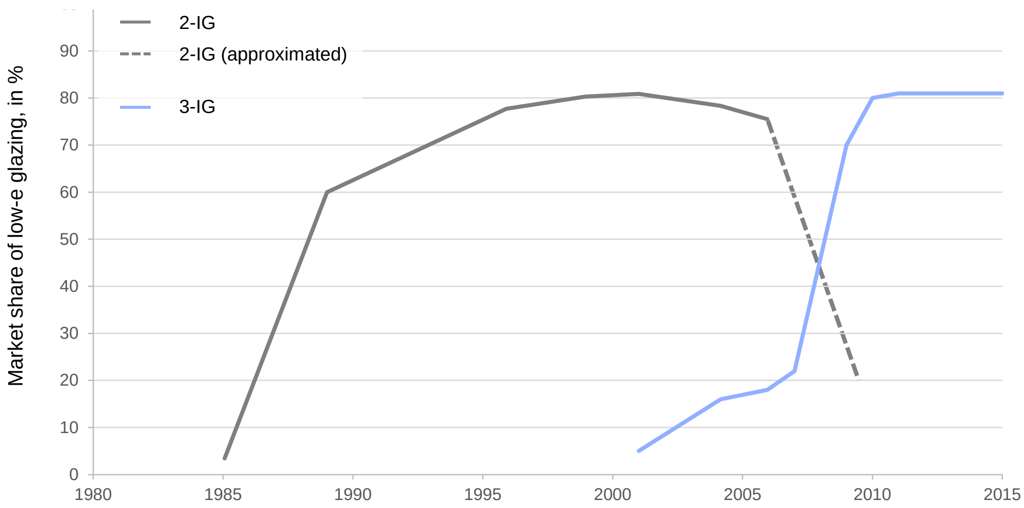

Figure 4: Diffusion of low-e glazing (2-IG/3-IG) in Switzerland, 1980-2015

4.1.2 Technology performance

Development of better insulating windows was mainly promoted as an initiative to better insulate the building envelope and therefore reduce heat loss. As observability is fairly low, the low-e coating of glass did not change the working principles of the product 'window' itself and low-e glazing is not perceived as an independent technology by processing industries and customers. Instead, technology performance in the form of KPIs are considered as relevant.

The standard window consists out of two main elements, glazing and frame. Consumers themselves only experience the product window and do not perceive glazing as a separate technology. Developers tried to improve the architecture of the whole window in order to reduce the u-value which was reported as the main key performance indicator (KPI). As changes of the frame design are considered to be negligible, the development for better windows was driven by the evolution of glass design and the modification of physical properties. Both technologies, 2-IG and 3-IG, consist of several constructive components, such as coating, glass, spacer and gas filling. The design of each element influences the parameter of the end product. However, applying low-e coating to the glass achieves the biggest u-value related improvements compared to changes of other constructive components. The u-values evolved with the technologies, from 2.1-2.4 W/m^{2}K for an uncoated, three-layered window design to 1.2-1.5 W/m^{2}K for the coated two-layered window (low-e 2-IG) to 0.7-1.1 W/m^{2}K for the coated three-layered window (low-e 3-IG). Before 2011, the manufacturers differentiated their products according to measurable physical properties, especially the u-value. With the collapse of the exchange rate in 2011, imports from low cost regions such as Eastern Europe and China increased, which led to an increasing price competition. Thereafter, differentiation between manufacturers was mainly marked by service (delivery times, just-in-time) and cost.

4.1.3 Technological system

Several main industries and actor groups are affecting the technological system of low-e glazing: the glass industry, building industry, window and facade producers, and public authorities. The amount of individual actors and actor types as well as the interconnectedness between them indicate a highly complex system. As of today, the glass industry itself is quite consolidated and consists of a small number of big multinational companies (between five and six manufacturers). The consolidation process started between 1990 and 1995 and ended between 2000 and 2005. Given the commodity nature of glass, the competitive environment between producers is regarded as aggressive and price driven, also due to rising imports. The few manufacturers face an asset-heavy production process, and are widely regarded as very innovative and proactive.

The processing industries (i.e., window and facade producers) are distinguished through many small actors (firms) which lack the capacity to oversee regulatory and technological developments. Professional associations, "Schweizerischer Fachverband Fenster- und Fassadenbranche" (FFF) and "Schweizerische Zentrale Fenster und Fassaden" (SZFF) filled this functional gap by informing their members about ongoing technological and regulatory trends and emerging products as well as by providing professional trainings. In addition, these associations are also involved in the formulation and distribution of private standards as well as the creation of public standards (such as "MuKEn") and mandatory labels (such as "Energieetikette für Fenster"). Yet, several experts questioned the importance of professional associations in the diffusion process of the low-e glazing technology in Switzerland, in comparison to rather powerful professional associations, as for example in Germany. Apart from the above, several public and private organizations influenced the technological system. The most important being the Minergie association, "Konferenz kantonaler Energiedirektoren" (KKED), cantonal "Energiefachstellen" as well as the "Schweizerischer Ingenieur- und Architektenverein" (SIA).

The analysis of system cumulates to three insights. First, a mature and innovative glass producing industry exists which proactively influences the system dynamics. Second, professional associations provide a link between the industries and are involved in the creation of policies. Third, the influence of actors in the decision process varies in magnitude and type. Our interviews indicate that architects and engineers have a great influence in the decision process and act as opinion leaders (see Appendix A for details).

4.1.4 Policy measures

After the oil crisis, first policy measures aimed at creating a regulatory environment for insulation of building envelopes in general and insulation of windows in particular. Before 1981, private standards, in particular the norm SIA 180, were the only regulatory guidelines to build windows. In 1981, canton Zurich launched a regulation for windows as one of the first big cantons. Following years were shaped by cantonal involvement in policy design until first standards at the national level were introduced in 1986 with *Musterverordnung* (MVO), and subsequently renewed in 1992 (MVO 92), in 2000 with *Mustervorschriften der Kantone im Energiebereich* (MuKEn) and renewed in 2008 and 2014. Dynamics between public and private standards led to a successive increase of regulatory stringency concerning the heating coefficient (decrease in u-value limits) as Figure 5 shows exemplarily for canton Zurich.

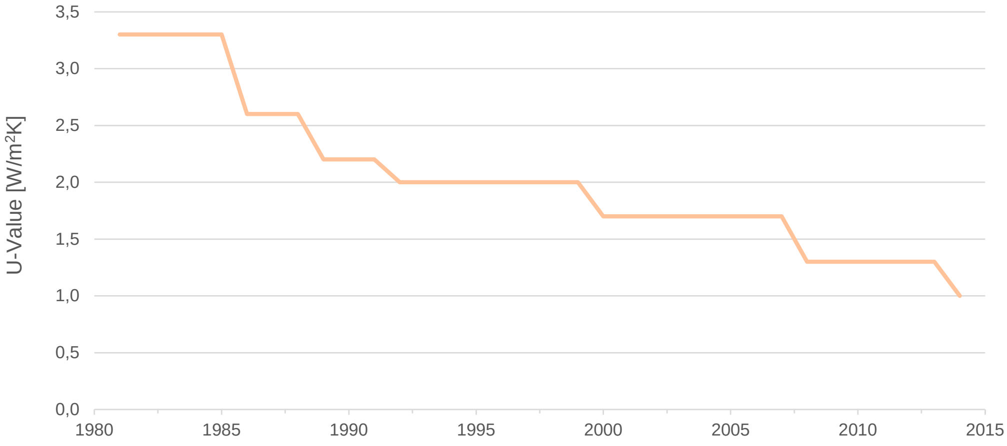

Figure 5: Development of u-value regulation in canton Zurich, 1980-2015

Due to its pioneer role in the implementation of policy, canton Zurich can be considered as a reference for cantonal public standards, particularly as a reference for the strictest standards at the national level. The voluntary building label Minergie, which was introduced in 1994, created a consciousness towards high performance buildings and was initially backed by the cantons Zurich and Bern. However, in 1998 with the foundation of the Minergie association political support was guaranteed by all Swiss cantons.

Minergie required the usage of 3-IG in order to fulfill the requirements postulated by the label. In 2001, the Minergie association introduced an additional voluntary label for the qualitative assessment of windows (namely Modul Fenster). Certification of windows through Modul Fenster became a standard which forced manufacturers to offer products compliant to these requirements. In the case of window specification, nowadays, the Minergie label becomes more and more obsolete, since requirements of public standards, in particular of MuKEn 2008 and successively MuKEn 2014, approached those of Minergie.

In 2006, a financial incentive program was enacted to foster insulation of building envelopes (so called Gebäudeprogramm) by supporting retrofit and construction of energy efficient buildings. The program was successively relaunched in 2010 due to the economic recession following the financial crisis in 2008. The extent of financial support for windows was defined according to private standards (hence, by u-value) and clearly promoted 3-IG (with 70 CHF/m^2) over 2-IG (20 CHF/m^2). Requirements for financial support, in terms of minimal exchanged window surface area, were successively increased and the amount of financial support diminished to 30 CHF/m^2 which therefore affected building as well as retrofit activities. The GEAK ("Gebäudeenergieausweis der Kantone") certificate was launched in 2009 as a voluntary measure to classify energy efficiencies of buildings. Six years later, in 2015, the mandatory label for the classification of energetic parameters in windows (Energieetikette für Fenster) was introduced on the national level by the Swiss Federal Office for Energy (SFOE).

Table 5 lists the main policy instruments and events in chronological order that influenced the diffusion of low-e glazing in Switzerland from 1981 to 2015.

Table 5: Overview of major policy instruments and events related to the diffusion of low-e glazing in Switzerland

Year(s)	Policy instruments / Events
1981	Regulation for windows in canton Zurich (as one of the first)
1986	Introduction of first public standard on the national level, "Musterverordnung" (MVO)
1992	Renewal of MVO
1994	Voluntary building label "Minergie"
1998	Foundation of the Minergie association
2000	Public standard on national level, "Mustervorschriften der Kantone im Energiebereich" (MuKEn)
2001	Voluntary label for qualitative window assessment ("Modul Fenster") by Minergie association
2006	Financial incentive program to foster insulation of building envelopes ("Gebäudeprogramm")
2008	Renewal of MuKEn
2009	Voluntary measure/certificate to classify buildings, "Gebäudeenergieausweis der Kantone" (GEAK)
2010	Relaunch of financial incentive program ("Gebäudeprogramm")
2014	Renewal of MuKEn
2015	Mandatory label for the classification of energetic parameters in windows ("Energieetikette für Fenster")

4.2 Illuminating the role of policy instruments

To recapitulate in brief, three types of policy instruments were applied in different stages of the diffusion: standards (private and public), labels (voluntary and mandatory), and financial incentives. During the diffusion of 2-IG, prevailing instruments were public and private standards. The launch of voluntary labels (Minergie, Modul Fenster) initiated the technology transition from 2-IG to 3-IG by spurring the demand for better performing window insulation. However, the importance of voluntary labels faded, especially with an increasing stringency of public standards (MuKEn), starting financial incentives (Gebäudeprogramm), and emerging mandatory labels (Energieetikette für Fenster). Over the whole diffusion process the importance of standards and their gradual adaptation towards higher stringency, that is, a step-by-step reduction of u-value limits, remains evident. These standards created a control and regulatory environment which other policy instruments could build upon.

A major prerequisite for the approach of gradually tightening the regulatory screws via standards lies in the characterization of the technology in scope and its quantification by means of a distinct measure or KPI. For building insulation in general and windows in particular, the heat transfer coefficient (u-value) is a well-established indicator whose value can be easily determined, thus it enables regulatory intervention both at the development side (technology-push) and the diffusion side (demand-pull).

5 Case 3: Comfort Ventilation

This section presents the case of the comfort ventilation technology. The structure of the section is in line with the previous cases, that is, description of the general working principles, retrospective analysis of diffusion data, technology performance, technological system, and policy measures, followed by causalities (drivers of diffusion and role of policy instruments).

Comfort ventilation is a stylized term[2] mainly used in Switzerland that was introduced by the Swiss Federal Office for Energy (SFOE) and primarily influenced by the Minergie label and its corresponding association. Defined by its application area, a comfort ventilation is a ventilation system for residential buildings and apartments with only minor technological differences to conventional ventilation systems for larger buildings, such as office buildings or industrial complexes. From a functional viewpoint the comfort ventilation comprises of two things: first, an air-intake and exhaust system (a ventilator and an air distribution pipe system), and second, a heat exchanger. The purpose of a comfort ventilation is to supply fresh air while reducing heat losses by exchanging heat between intake and exhaust air flow. Several high-end products additionally include a humidity or moisture exchanger in order to overcome arising problems concerning air humidity. With better insulated building envelopes (cf. progress in facade and window insulation), the need for air exchange becomes relevant for the inhabitants, as fresh air provides higher comfort, and for the building itself by preventing mold formation. Therefore, the comfort ventilation technology directly complements insulation measures that increase efficiency. In comparison to a regular manual exchange of room air – besides the time-consuming manual effort of airing –, the comfort ventilation technology allows to save around 30% [27] on heating energy and up to 70% on ventilation losses [28], thus truly represents an energy efficiency innovation.

5.1 Retrospective observations

5.1.1 Market and diffusion

Extensive interest in comfort ventilation systems started to spread in Scandinavian countries in 1985 since heat loss through air exchange was mainly caused by a colder climate and reinforced the advantages of installing comfort ventilation technology. In Germany, comfort ventilation systems started to diffuse in the 1990s whereas Switzerland experienced an emerging demand in 1995. Prior to that, singular projects were realized in Switzerland deploying a comfort ventilation. The demand for comfort ventilation systems grew from the mid-1990s on with initial sales at a low annual level of 89 units (1995). Considerations to install comfort ventilations in larger scale projects boosted annual sales to 1356 units in the year 2000. Consequently, a pioneer market developed between 2000 and 2005 which later evolved into a mass market. According to the experts' statements, a mass market started between 2004 and 2007. Between 2005 and 2011 sales increased rapidly with annual growth rates of up to 53% (2005). In the following years, relative sales growth stagnated, reaching today's market share of slightly above 30% for new-build apartments.

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[2] Other terms in use are *residential ventilation systems*, *small ventilation systems* and *controlled domestic ventilation*..

Figure 6 shows the market share of comfort ventilation systems in Switzerland, from 1985 to 2015 based on data from BFS and energie-cluster.ch. The market share is formulated as the ratio of annual units sold (<350 m^3/h) to the annual number of new-build apartments.

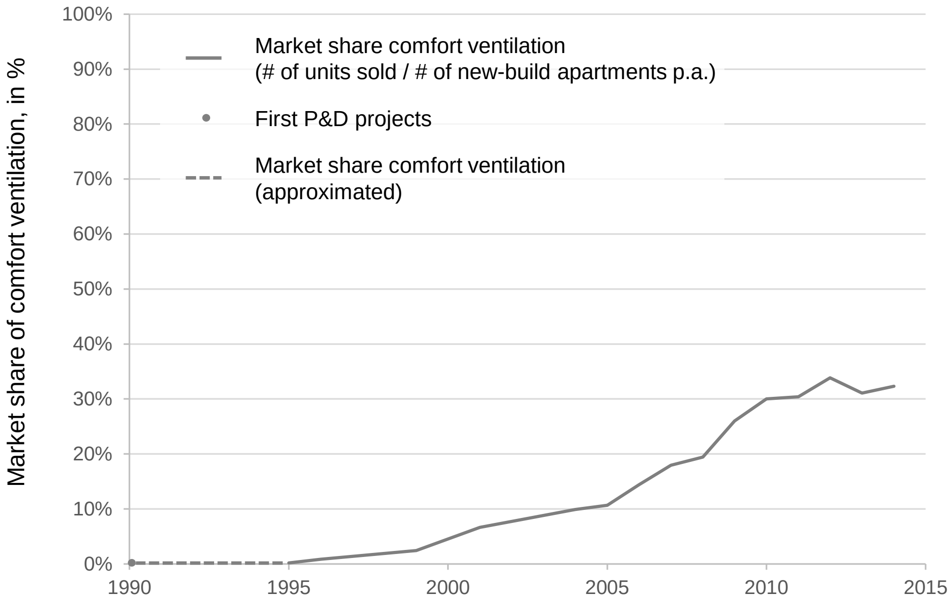

Figure 6: Diffusion of comfort ventilation systems in Switzerland, 1990-2015

5.1.2 Technology performance

As briefly stated above, the development and diffusion of the comfort ventilation technology are strongly linked to the technological development in the field of building envelope insulation. The massive improvements in the insulation of the building envelope were a result of the better insulation of its components, that is, better wall, window, and door insulation. This progress affected the demand for comfort ventilation. On the one hand, improving insulation also triggered an increasing air sealing. Problems arising from this issue, such as comfort loss due to bad air quality or building damages (mold due to high air humidity), can be solved by installing a comfort ventilation. On the other hand, comfort ventilation was considered a necessary complement to further reduce building energy consumption by exploiting the insulation measures in the future.

The technological trajectory of comfort ventilation systems is determined by its predecessor, standard ventilation systems, in large-scale applications. With similar technical characteristics (e.g., same filter qualities), the comfort ventilation is a good example for technological downscaling. During the last 20 years several technological developments enhanced the comfort ventilation, both on the side of the air intake and exhaust system, as well as on the side of the heat exchanger. Initial systems were equipped with parallel heat exchangers and regular ventilators, thereby achieving energy recovery rates of 50 to 60%. Over time, electronically commutated (EC) motor were incorporated in ventilators and counter-flow heat exchangers replaced parallel heat exchangers. First comfort ventilation systems that implemented both technical innovations were commercially available by 1999. The former technological enhancement (EC motor) was quickly adapted by most manufacturers and was broadly established in 2005. The successful establishment of the latter enhancement (counter-flow heat exchanger) took several years longer until 2010.

As of today, comfort ventilation systems have energy recovery rates of 80 to 90%. However, the energy recovery rate as an indicator for performance is reported to not affecting the decision process (see Appendix B for details). Besides improving energy recovery rates, there were also improvements in the air distribution system. Semi-flexible plastic tubes were introduces which facilitated encasing the distribution system in concrete.

On the one side, the core technology, that is, ventilator and heat exchanger, is nowadays well understood and feature reliable and good quality. On the other side, quality issues (hygiene and noise exposure) might arise during the installation of the comfort ventilation and its corresponding distribution system. These quality issues are subject to continuous improvement but low margins sometimes compromise the operational quality of manufacturers and installers, thus impacting the quality comfort ventilation systems.

5.1.3 Technological system

The technological system of the comfort ventilation technology is mainly characterized by three industries: the ventilation industry (with manufacturers and installation firms), the sanitary industry (with installation companies), and the building industry. The ventilation industry comprises 20 to 30 manufacturers from which only five with high relevance with regards to market share. Common to the formative phase of an emerging industry, manufacturers experienced a phase of turmoil, followed by a consolidation phase. Prior to that, the entries of cross industries from adjacent branches (sanitary industry) shaped the formative phase, as the ventilation industry displayed initial restraint towards the comfort ventilation technology (due to a deficiency of skilled workforces). The fact that other industrial branches, such as the sanitary installation industry, gained most of the market shares due to existing synergies however, prevented the optimal use of technological know-how inherent in the traditional ventilation industry.

In the early 2000s, large international firms entered the Swiss market, followed by price declines (which resulted in decreasing product qualities).The manufacturers addressed this by two separate approaches, either offering low-cost products or a differentiation through service and quality. In the latter approach, they relied on training programs for executive actors (such as architects, planners, and installers) in order to raise the comfort ventilation’s quality in particular installations. However, responsiveness of executive actors for training programs was rather low.

5.1.4 Policy measures

Policy support for the comfort ventilation technology started in 1990 with first pilot and demonstration project, an energy autarkic housing complex constructed in Waedenswil by the department for energy Zurich. Also in 1990, the SFOE offered a performance guarantee for comfort ventilation systems. In the following years the SFOE became more and more involved and launched in 1990 the public leadership program “Energy2000”, which was followed by “Swiss Energy” in 2000. As a consequence, other pilot and demonstration projects were implemented by the SFOE, such as in 1995 (Riechen), 1996 (Winterthur), 1999 (Nussbaumen), 2000 (Daellikon) and 2002 (Staefa, Dielsdorf and Renggli). In the same vein, SFOE launched an awareness raising campaign by proactively distributing project specifications to potential planers and end customers.

In 1994, the voluntary Minergie label was established by members of the department for energy Zurich. Even though, Minergie promoted the installation of comfort ventilations, its building certification did not explicitly prescribe their installation. Yet, Minergie requirements for energy consumption rates were difficult to achieve without a comfort ventilation system. Nowadays, about 98% of Minergie certified buildings feature a comfort ventilation system. Minergie’s takeover by cantons Zurich and Bern in 1997 and the subsequent compliance of the remaining cantons in 1998 indicated a rising support of the public sector towards the use of the comfort ventilation technology. In addition, several cantons started public leadership projects such as canton Basel (retrofit program) and canton Zurich. In 2011, the Minergie associaton launched the voluntary product label “Modul Komfortlüftung”. To comply with this certification, comfort ventilations were systemically evaluated by both designated producers and installers. A similar label “Deklaration” was created by the Energie-Cluster in 2012.

For a long time, private standards were underrepresented with ventilation but not comfort ventilation specific norms, such as SIA 382/14 and SIA 382/25. This lack was partly remedied with the release of the instruction sheet to SIA 2023 in 2008. With the launch of the public standard MuKEn in 2000, public involvement in the creation of a regulatory environment increased. It restricted the share of consumed energy from fossil energy carriers to 80%. Subsequent versions of MuKEn (2008 and 2014) lowered the limits for energy consumption and referred to the use of comfort ventilation systems as a standard solution for achieving those limits.

Table 6 below lists major policy instruments and events in chronological order affecting the diffusion of the comfort ventilation in Switzerland from 1990 to 2012.

Table 6: Overview of major policy instruments and events related to the diffusion of comfort ventilation in Switzerland

Year(s)	Policy instruments / Events
1990	First pilot and demonstration project (energy autarkic housing complex, Waedenswil)
1990	Performance guarantee offered by SFOE
1990	Launch of Energy2000 (SFOE), public leadership program
1994	Voluntary building label “Minergie”
1995-2002	Further demonstration project by SFOE in Riechen, Winterthur, Nussbaumen, Daellikon, Staefa, Dielsdorf and Renggli
2000	Launch of Swiss Energy (follow-up program of Energy 2000)
2000	Public standard on national level, “Mustervorschriften der Kantone im Energiebereich” (MuKEn)
2008	Release of instruction sheet to SIA 2023 ("Lüftung in Wohnbauten”)
2008	Renewal of MuKEn
2011	Launch of the voluntary product label “Modul Komfortlüftung” by Minergie associaton
2012	Launch of voluntary label “Deklaration” by Energie-Cluster
2014	Renewal of MuKEn

5.2 Illuminating the role of policy instruments

The above outlined compilation of policy measures point to three distinct phases. A starting phase between 1990 and the early 2000s that was characterized by pilot and demonstration projects as well as information campaigns. During this time, policies aimed at knowledge creation and building up initial awareness for the innovation, mostly targeted architects and planners. The SFOE played a vital role (as initiator for P&D projects, distributor of information) in this phase, the beginning of the diffusion process.

The second phase, roughly from 1998 to 2008, was determined by the influence of the voluntary Minergie label as it paved the way for a successful diffusion by creating the necessary market demand. The demand was triggered to a large extent in building-owners by changing the perceived values (i.e., increase in comfort and property value) of technology. During this phase, SFOE’s contribution to an accelerated diffusion declined due to the rising importance of the Minergie label and its positive impact on the diffusion. In addition, public support of Minergie created the necessary trust towards the innovation.

The last phase, between 2008 and 2015, experienced a strengthening of public standards, mainly MuKEn. MuKEn supported the market formation activities of the voluntary labels (Minergie/ Modul Komfortlüftung, Deklaration) by generating additional demand for the comfort ventilation technology. Our interview findings indicate that the influence of the public standard MuKEn outran Minergie as the main influencing policy and truly spurred the diffusion.

6 Overarching findings

This section describes the encompassing findings that we derived from the case study analysis. First, three archetypes of innovations are presented that we extracted from the different characteristics of our case study technologies. For each of the archetypes we show in which manner policy support ideally needs to be tailored to efficiently accelerate the diffusion of each archetype. Then, we outline the effects of potential mismatches of policy support and innovation archetype and illustrate with examples.

6.1 System maturity matters: policy prescriptions

Analogous to the process of ageing humans, we observed different maturity stages for the technological systems of our case study innovations in scope, viz. infantile, juvenile and adult. In contrast to biological age or mental development, this distinction is based on the maturity stage of the surrounding technological system that the technology is embedded in, thus it does not have to correlate with calendrical life. A system consists of certain structural elements: actors, institutions, networks (cf. technological innovation system [29]), thus the degree to which these elements are developed and seamlessly connected determines a system's maturity stage. As a matter of course, technologies and their related systems along with the diffusion undergo a dynamic process, that is, similar to humans, they grow and reach the next stage at one point in time, even though the process might not be as linear over time as it is usually the case for human beings. Based on our case study observations we notice that the ideal mix and sequence of policy instruments to efficiently accelerate the diffusion of low-carbon innovations is a function of both, the maturity of an innovation's technological systems and the diffusion stage. It needs to be pointed out that both dimensions underlie dynamics, that is, maturity and diffusion change over time. In addition, admittedly, both dimensions are interrelated to a certain extent meaning that an innovation embedded an infantile technological system will encounter great difficulties in achieving high diffusion rates regardless of the expended policy efforts. Therefore, we argue that especially in early diffusion stages it is crucial to identify the maturity stage of an innovation's technological system before policy intervention is designed, and then, reevaluate system maturity on a regular basis to adapt policy measures accordingly over time.

Figure 7 illustrates our suggested framework by combining the stylized diffusion (S-)curve and the maturity of the technological system, ranging from low (infantile) to high (adult). We touch upon each of these three archetypes (infantile, juvenile, adult) and the role of policy in the following subsections.

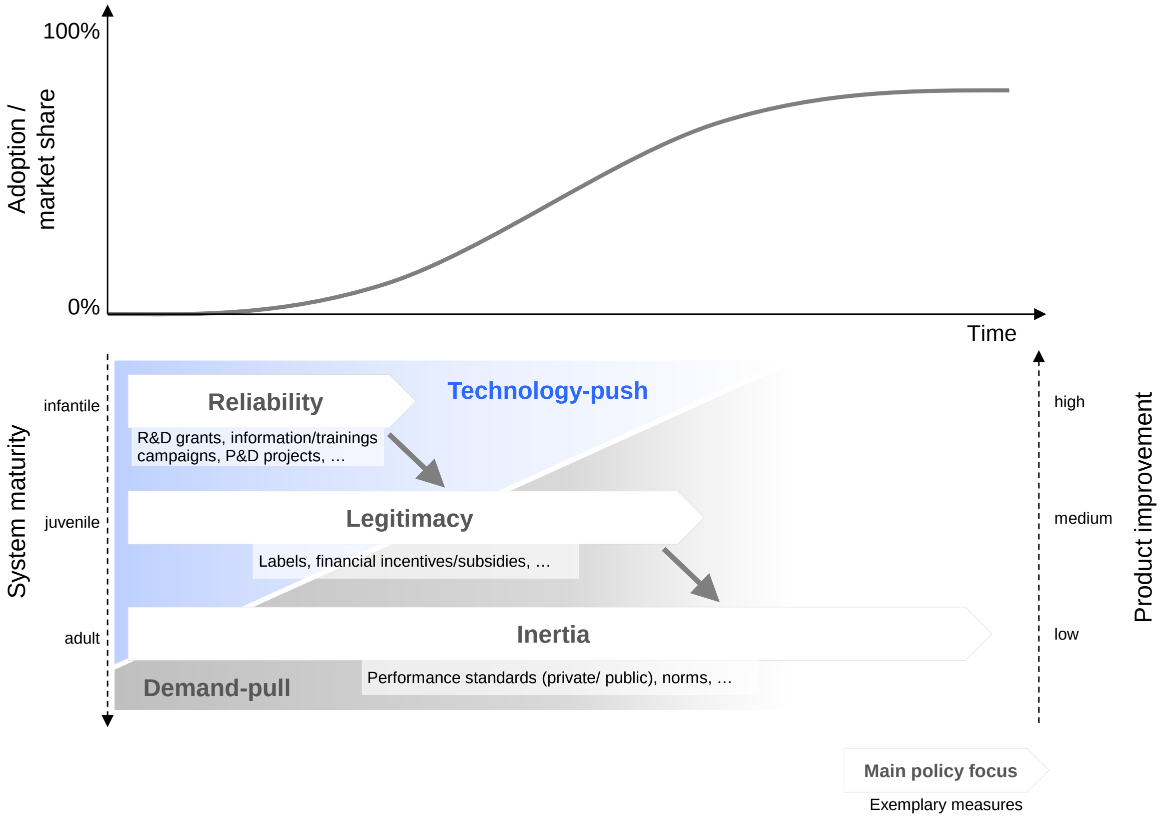

Figure 7: Framework for efficient policy support in accelerating the diffusion of low-carbon innovations

6.1.1 The Infantile

Innovations that are embedded in an infantile technological system face challenging conditions. After its development, this new type of technology sees itself confronted with competing, incumbent alternatives with high market power that have shaped the market and the surroundings alike for many years. The innovation itself still faces teething problems (such as compatibility issues, limited lifetime, malfunctioning) and lacks elementary support functions by the system elements. That is, actors are not yet familiar with that new type of technology, institutions are not established and networks are not (properly) developed. Policy support for innovations with an infantile technological system needs to put emphasis on technology-push measure to increase reliability and strengthen knowledge development, thus coping with quality issues. Potential measures that help to reach these targets are, for example, R&D grants, testing facilities / field tests, P&D projects, conferences, training/information campaigns, guidelines, trade fairs, and associations. Applying (some of) these measures allows to nurture the infantile system and eventually evolve it into a more juvenile stage, a prerequisite for capturing considerable market share and pushing diffusion more and more towards a mass market.

6.1.2 The Juvenile

A juvenile technological systems implies for innovations that actors, networks, and organizations are already present and partially familiar with the advent of the new technology. Several firms arranged production capacity accordingly and are able to manufacture it, albeit market consolidation and mass production has not fully started. There still might be rivalling technologies and consciousness of actors and organizations towards the innovation can be limited. Yet, the innovation itself mastered initial complications and proves itself in a fairly reliable state towards potential customers at the different decision levels. In contrast to the predominant technology-push measures in the infantile system stage, here the policy focus shifts more towards demand-side instruments to create legitimacy for the innovation. This can be accomplished, for example, by making use of existing, well-established vehicles such as labels (either voluntary or mandatory) or certificates, and by this putting the innovation in the passenger seat profiting from an accelerated diffusion pathway. Other possible measures are financial subsidies or incentives that directly stimulate demand on the consumer level (which can still be versatile). Once an innovation’s technological system has grown up from a juvenile to an adult stage, other measures might be more qualified to further trigger its diffusion.

6.1.3 The Adult

An innovation that finds itself in an adult technological system can be considered highly favored with regards to the ease of supporting its diffusion. At the system level, all structural elements are well advanced, that is, actors, networks, and organizations are established and highly aware of the innovation’s emergence. The market shows already a more consolidated picture and most firms have adapted production capacities to be able to manufacture the innovation in a highly efficient (mass production) manner. The innovation itself is highly reliable and the few competing technologies, if at all, mostly occupy very specific niches and do not represent serious competition. The necessity for technology-specific support further decreases from the infantile over the juvenile to the adult system stage and demand-pull measures are most efficient in spurring diffusion. Potential measures are regulatory, performance standards (public or private) and norms that help to overcome the system’s inertia towards the innovation. These standards can then be gradually adapted, towards higher stringency, in line with the innovations foreseeable technical performance. By gradually raising the regulatory bar, the innovation needs to improve (incrementally) to meet the requirement but in return benefits from the demand pull by becoming obligatory and thereby diffuses efficiently.

6.2 Avoiding inefficiency

In order to efficiently accelerate the diffusion of low-carbon technologies, we distilled a few mechanisms from our case study observations and derived recommendations in the section above. However, we also want to briefly highlight the effects of mismatching policy measures to innovations embedded in technological systems with different maturity, thereby causing large inefficiencies (economic, time, and/or environment wise). Assuming the case of an innovation with an infantile technological system that is tried to be pulled into the markets, for example by labels or regulatory standards. With a premature market pull before quality issues are eliminated and reliability is established (i.e., system elements and functions are underdeveloped), the innovation runs into high risk of reputational losses on the consumer side. In doing so, the policy maker jeopardizes acceptance of the innovation in the short- and long-term alike. In addition, a premature market-pull can create technological lock-in while superiority of competing technologies is hardly foreseeable. A potential example for the latter is regulation EC 244/2009 by the European Union (EU) that specifies the gradual phase-out of incandescent bulbs from 2009 to 2016. As the two competing technologies, compact fluorescent lamp (CFL) and light-emitting diode (LED), were in an emerging phase, the regulatory directive favored the CFL technology, being a few steps ahead of LED by that time, and thereby creating an intermediate lock-in to CFL. Still, in the long run, LED proved to be the more efficient technology with less environmental impact (cf. mercury). However, it would require further examination to assess the extent to which LED might still have benefited from this regulation, for example, because of its cheaper and non-poisonous competitor, the incandescent bulbs, being ruled out.

Now, picturing the case on an innovation with a highly mature (= adult) technological system. Here, excessive policy support to increase reliability and legitimacy, e.g. via R&D grants, labels, would result in a waste of public funds, whereas diffusion could be spurred faster and less expensive. With these illustrations we aim at underlining the necessity of adequately assess an innovation's system maturity and its diffusion status to tailor policy instruments accordingly.

7 Discussion

This section discusses the (overarching) findings from our case study analysis by first, introducing implications. Secondly, we state limitations and discuss how they could be addressed. Finally, we conclude with a short summary and list our core contributions.

7.1 Implications

The findings from our case study observations imply that policy makers, once they decided on an innovation that qualifies for public support[3], need to thoroughly assess its surrounding technological system. This way, current bottlenecks for an efficient diffusion can be easier identified and policy instruments can be selected and tailored accordingly. Choosing adequate measures to accelerate the diffusion still remains a challenging task, as other factors, such as external events/shocks, also shape diffusion dynamics of a technology. However, our distinction regarding degree of maturity of technological systems (infantile, juvenile, adult) provides a guideline for policy makers on what combinations of policy instruments and technological system can work and which should be avoided. For example, an innovation with an infantile system responds to extremely different measures than one in an adult context. In section 6.1, we laid out some examples, based on our analyzed technologies, of which combinations can be successful, and in section 6.2 we stated combinations that were less successful and led to inefficiencies in the diffusion process.

Besides policy makers actively designing policy intervention, decision makers within a technological system can in turn passively exert influence, for example, by first identifying key bottlenecks themselves and then signaling it to the corresponding public bodies. This way, they would help to ease the effort for

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[3] The decision on how (e.g., according to which criteria, sense of urgency) to select technologies that deserve external assistance to prevail on the market is another large, but different debate that cannot be touched upon in this article.

policy makers in assessing system maturity and diffusion status which is a prerequisite for selecting an efficient set of measures to accelerate the diffusion.

7.2 Limitations & further research

The limitations of this study are fourfold. First, the case selection limits the findings because 1) the sample size, and 2) the selection of only successfully diffused technologies. Our sample size of three case study technologies might be suitable for creating an explorative understanding of the case specific diffusion dynamics. However, it restricts generalizability of the findings to a broader range of technologies, due to a potential selection bias. Besides the sample size, the sample strategy of only selecting ‘success stories’ (i.e., well diffused technologies) raises the issue of a pro-innovation bias. To address the limitations regarding case selection, it would be beneficial to assess additional case study technologies (more and ‘failure stories’) in the future in order to examine the robustness of our findings.

Second, and closely related to the case selection, is the nature of innovation we investigated. We limit our study to product innovation, thus only considering tangible, physical products. In doing so, we disregard service innovation that can equally facilitate energy efficiency and decarbonization of society. Future research could be very insightful in examining whether there are – and if so, what kind of – differences between physical product innovation and intangible service innovation.

Third, the relation of policy measures on an innovation’s diffusion cannot be observed in laboratory conditions, meaning that isolating the influence of other factors is hardly possible. For instance, external factors, such as the oil crisis, nuclear disaster, can contribute to the diffusion dynamics in both, a positive and a negative way. Dismantling and quantifying each factor’s impact is a very complicated task, and calls for further, more quantitative research. In our study, we rely on the statements by the interviewed experts describing the relations and mechanisms that we laid out above.

Lastly, we stumbled across different concepts in defining a radical innovation. An innovation can be radical in three different ways. First, the product itself, in line with Murmann and Frenken [18], can be characterized by a high performance improvement and/or large amounts of new knowledge. Second, the production process of the new product can be of radical nature (e.g., new procedures, assets). Thirdly, the product can be radical regarding its customer behavior (e.g., complex, compatible). Exploring whether these different kinds of radicalness influence the selection of efficient policy measures to accelerate the diffusion might be another promising avenue of future research.

7.3 Conclusion

This report aims to understand the dynamics in the diffusion process of energy efficient technologies. In particular, its focus lies on policy intervention and grasping mechanisms that lead to an efficient acceleration in the market diffusion of low-carbon innovations. To do so, we analyzed the historical developments in the diffusion of three selected technologies, heat pump, low-e glazing, and comfort ventilation technology. We chose Switzerland and its policy context, as it proves to be the (or among the) lead market(s) for the diffusion of these technologies, thus by holding political and contextual environment constant we try to capture the integral policy drivers. To retrace the developments retrospectively, we collected archival data, conducted expert interviews, and then analyzed both of them.

We find that the maturity of an innovation’s technological system along with its diffusion status affects the choice of policy instruments. We show that with a weakly developed system, policy needs to first foster mainly industry-specifically (e.g. via R&D grants, conferences/fairs, P&D projects) to enable the industry to manufacture the technology at a quality and reliability level that allows to compete against default technologies. Once the system reaches a reasonable maturity level (juvenile), other market dynamics, such as labels, are an efficient measure to stimulate demand by creating legitimacy, thereby benefiting from the higher demand of the label as a whole. A very mature system allows to apply performance standards (e.g., u-value limits) and gradually adapt them over time.

This work contributes to the existing literature by combining aspects of diffusion theory with environmental policy and technological evolution. Apart from that, it aims at supporting policy and decision makers alike in understanding the dynamics of policy intervention and the diffusion of low-carbon innovations in the pursuit of a more energy efficient and decarbonized society.

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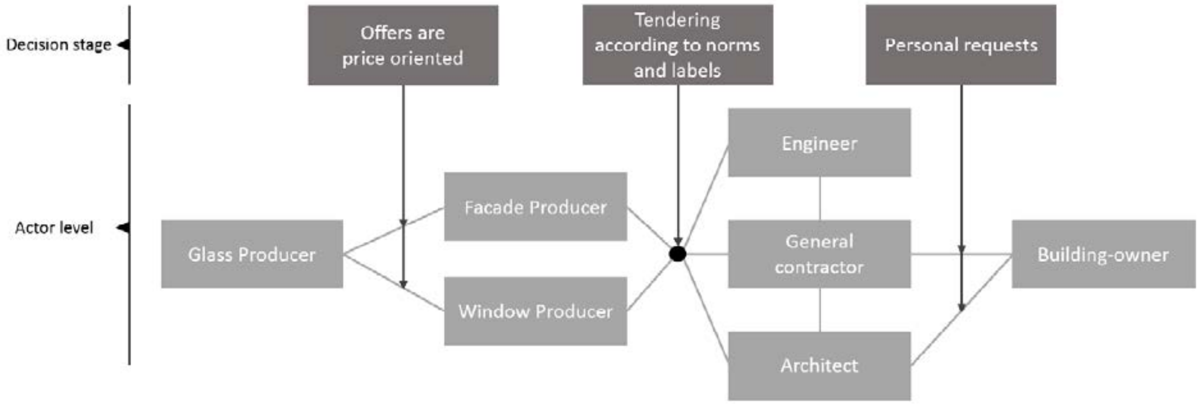
Appendix

Appendix A

Actor-network and decision stages for the adoption of low-e glazing technology (2-IG/3-IG)



Appendix B

Actor-network and decision stages for the adoption of comfort ventilation technology