Comparative analysis of energy efficient technology innovation in buildings: the case of passive houses in Germany, Sweden and China

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Abstract

Buildings account for almost 30 % of global CO_2 emissions (IEA, 2010). Large savings in energy use (75 % or higher) are possible in new buildings through better designs (IPCC, 2007). However, there is also institutional inertia and other barriers in the building sector that hinders the introduction and diffusion of technologies and new practices. The mechanisms that support or hinder introduction and diffusion of energy efficiency in buildings can be analysed from an innovation system perspective. Passive houses, as an example of a high efficiency standard, are starting to be more common in some European countries.

We analyse here the development and innovation diffusion of passive houses in pioneering Germany, the 'second-mover' Sweden, and China which is in the preparation phase, from a Technological Innovation Systems (TIS) perspective. The TIS approach enables us to analyse the passive house innovation process from a niche market to becoming the norm. Our aim is to extract knowledge for future policy strategies for deep energy efficiency in buildings. For that purpose we assess the structures and functions of the innovation systems and identify the system drivers and problems in the three different countries.

The results show, for example, the important role of certain actors, such as intermediary organizations. The mainly bottom-up driven development in Germany and Sweden may in China be complemented with top-down governance approaches in the future, which can create considerable scale-effects. This first-time application of the TIS-perspective to energy efficiency in buildings in a developing country demonstrates the usefulness of the approach. It suggests that policy for building energy efficiency in China should adopt a broader strategy, go beyond building codes and demonstration projects, and seriously consider how the innovation system can be strengthened in all its important functions and adapted over time.

Introduction

Buildings account for about 40 % of primary energy consumption in most countries. With large saving potentials, energy efficiency in buildings is one of the key and least expensive measures to meet a range of climate and energy policy objectives (IEA, 2010; IPCC, 2007; Joachim Morhenne, 2007). One example, the passive house (PH) concept, represents one of the highest efficiency standards to date, with 90 % lower space heating demand compared with typical central European buildings (Feist, 2007). In this paper we use PH as a case for the purpose of extracting knowledge for future policy strategies to make a transition to high energy efficiency in buildings. Although the PH concept may not be the 'best' solution in all situations it represents a front-runner concept that can lead the way to higher efficiency standards and be a stepping stone to future zero- and plus-energy buildings.

Many countries are actively trying to transform building energy performance. For example, China aims to save 116 Mton of coal equivalents (3.4 EJ) in the building sector during the 12th Five-year plan period (2010–2015), 1.3 EJ of which comes from energy efficiency in new buildings (MOHURD, 2012).

The European Commission requires that new buildings should be "near-zero energy" from 2020 and onwards in the recast of the Energy Performance of Buildings Directive, EPBD2 (European Parliament and the Council of the European Union, 2010). In frontrunner countries such as Germany and Sweden, the targets include that the building sector should be operating without fossil fuels in 2020.

The PH concept existed already when our ancestors adapted to survive in the environment of their time with limited technical and other resources. For instance, the Chinese traditional buildings emphasize the south-orientation to gain light and warmth (Ken & Perlin, 1980). The related passive solar building designs were developed in the United States in the 1960s and 1970s. However, the modern PH concept was introduced in 1980s by the Swedish professor Bo Adamson and Wolfgang Feist, the founder of the Passive House Institute in Germany. One of Adamson's original ideas in the 1960s was to simplify and reduce the costs for heating installations in Swedish houses through better insulation.

The market development in Germany started to take off in 2000–2002 and in Sweden about five years later. As a result, Germany is home to about half of the built PH dwellings in Europe (Lang, 2010). In China, however, it has just started with a limited number of experimental and demonstration buildings. Today, the barriers to diffusion of PHs or other high efficiency buildings are not so much due to lack of technology, but rather lies in the information and knowledge gap, institutional inertia, lack of political will, and similar factors.

A better understanding of the PH technological innovation system (TIS) and prospects for energy efficiency is particularly important to China. Every year, half of all new buildings in the world are built in China alone. Approximately 300 million people in China are expected to migrate from rural to urban areas in the next twenty years. This, together with the increasing indoor comfort levels in the south of Yangtze River where district heating is not available, creates continued demand for urban dwellings and their heating.

In the literature, a number of studies have given attention to the technology and policy aspects of energy efficient buildings (International Energy Agency 2010; Zhou and Lin 2008; Badescu and Sicre 2003; Intrachooto and Horayangkura 2007; Boqvist 2010). There has also been increased research on innovation aspects in the field of sustainable development in recent years. Many of these studies focus on the formation and further development of renewable energy technologies in the context of innovation system structures (Johnson & Jacobsson, 2003; Markard & Truffer, 2008a; Mlecnik, 2011; Sandén, Jacobsson, Palmblad, & Porsö, 2008), system functional analysis (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008; M.P. Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007), Multi-Level Perspective (Markard & Truffer, 2008b) and Strategic Niche Management (Raven & Geels, 2010). However, efforts to integrate innovation theory and building energy efficiency remains quite limited with some exceptions by Eberhard Jochem (2009), Halse (2005) and Ornetzeder and Rohracher (2009).

To bridge the research gap, our paper adopts a TIS framework with a focus on the system functions, to analyse the PH development process and assess the functions that enabled PH technology to diffuse, or prevented it from doing so. By looking at the different PH market penetration levels, a comparative study is made to understand the preparation, introduction and growth stages of the technology diffusion in China, Sweden and Germany respectively, and discuss policy implications and directions for future policy.

Theoretical framework and methodology

In the last half century, innovation theory has evolved from Schumpeter's linear model of innovation, to a systemic approach, by arguing that it more accurately reflects the complexity and interdependency of innovation processes, including uncertainty, learning curves, institutional structures, actor interaction, and system feedbacks, rather than simple R&D input pull or demand pull. It provides a role for policy to improve the institutional framework and the opportunities for interactions, and thereby provide better incentives for innovation (Greenacre, Gross, & Jamie, 2012). The PH concept can be seen as an incremental innovation by mainly combining existing technology components and a basic TIS-approach appears to provide a useful analytical framework.

Technology innovation systems (TIS), as a subset of innovation systems, defined by Carlsson and Stankiewicz (1991) is 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. The approach studies technology development structures (institution, actors, network) and processes, and explains why and how new ideas have diffused into a society, or failed to do so. TIS as an analytical tool has been further elaborated with the introduction of system functions which are listed and explained in Table 1. Not every system function is as important as other system functions in each innovation stage (Luo et al., 2012). For example, knowledge development or technology transfer are the most important system functions at the pre-development stage. To support market development, entrepreneurial experimentation, resource mobilization and guidance of search become more critical at the later stages. The studied countries are in different development phases. In the case of China, technology transfer as an event type of "knowledge diffusion" is specifically discussed. This is of particular importance for the innovation performance of developing countries (Li Liu, 2011). Functions can also interact with each other and create virtuous or vicious cycle that lead to the diffusion or slow-down of a new technology (Marko P Hekkert & Negro, 2012). Societal and environmental goals may legitimize government R&D spending. This, in turn, leads to knowledge development and new or improved technologies. Advocacy coalitions may function as catalysts to create legitimacy or to resist the change. Each function includes several event types, and one event can sometimes contribute to several functions. The event types under each function category are listed to avoid ambiguity.

Our analysis and evaluation of innovation system structure and functions is based on information from various publications (e.g. research articles, reports, and websites), information gathering at conferences, and several expert interviews in the target countries. More specifically, 10 experts were interviewed in Sweden and China, only a couple of interviews were made in Germany since the area is better documented than the other

Table 1. Passive house technological innovation system functions and the implication (adapted and revised from Suurs 2009; Bergek et al. 2008; Liu 2011).

Functions	Event types	Actors involved
1. Entrepreneurial activities	Demonstration/pilot, building components development	Developer, Architect, Engineer, component manufacturer
2. Knowledge development	R&D, education, learning-by-doing	University, research institute, Architect, Engineer, Craftsmen
3. Knowledge diffusion	Conference, workshop, NGO meeting, training, social networking, technology transfer (in developing countries)	All actors
4. Guidance of the search	Energy targets, building codes, social norms	Government, developer, residents
5. Market formation	Finished projects, geographic distribution and subsidies	Government, developer
6. Resource mobilisation	human capital, components availability	Architect, Engineer, component manufacturer, financial body
7. Support from advocacy	Lobbies	Key players

two countries. The experts are mainly from universities, industry, passive house institutes and some key actors who were involved in the first passive house projects in these countries.

Technology development

The building sector is known to be a relatively conservative industry with low innovation rates. Innovation usually occurs when new methods are needed to enable something to be constructed quicker, cheaper, or in different conditions (Davey-Wilson, 2001). Sustainability as a driver is a recent addition to the traditional supply, user or market type drivers of innovation. PH represents good practice from a sustainability perspective and is different from other energy efficiency concepts in that it has a relatively clear definition. According to the German Passive House Institute, a Passive House is a building for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to fulfill sufficient indoor air quality conditions (DIN 1946) without a need for re-circulated air. In the central European climate, the annual space heat requirement is 15 kWh/m^2/a and overall primary energy requirement of 120 kWh/m^2/a, including the preparation of hot water and all household appliances. In Sweden, the peak load for space heating is required to be less than 10–16 W/m^2 so that the ventilation system can also be used for space heating (Janson, 2008). The definition of a passive house standard in China is still under discussion. However, the name "non-source houses" instead of "passive house" was adopted by Beijing non-source buildings planning and design institute since "passive" is negatively perceived as inactive and inert in Chinese (Lingxiang Liu, 2010).

The concept is a combination of engineering innovations which emphasize super insulation and highly efficient ventilation system equipped with heat recovery. The initial design of PH intended to reduce the space heating by 90 % compared to a conventional new building in Germany around 1991. Initially the focus was on building components and air-tightness whereas design solutions for summer conditions and building aesthetics were not important considerations. As a result of technology development, improved indoor climate, increased availability of PH components and knowledge gained through learning-by-doing, together with government subsidies, it is now possible to build PHs at a competitive cost or even without extra cost when considering the building life cycle and future energy costs. The concept has been proven in both single- and multi-family dwellings, in new and renovated buildings, and it has also been adjusted according to varying climate conditions and building aesthetics.

The PH concept coexists with other ones such as EnEV, RAL low-energy houses in Germany, Minienergihus, zero-energy houses, energy-plus buildings, and zero emission buildings. LEED and green building standard is used in China, although these criteria cover broader environmental aspects and are not oriented to energy efficiency in particular. Hermelink (2009) and Mahdavi & Doppelbauer (2010) have shown that passive houses outperform other low energy buildings with lower CO_2 emissions and primary energy supply. The higher emissions in the construction and maintenance/repair stages can be offset by the low emission during operation, based on life cycle analysis. It should be noted that this paper does not advocate any specific standard, brand or definition. PHs are used here as a case but the design principles behind passive house are common to essentially all energy efficient buildings: the use of super insulation and high air-tightness.

Innovation structure

The innovation structure covers institutions, actors and networks, and technology (discussed above). The evolution of institutions is key to innovation systems. As defined by Edquist and Johnson (1997), institutions are the sets of common habits, routines, established practices, rules or laws that regulate the relations and interactions between individuals and groups. Institutions can be formal and informal (North, 1990). The formal institutions in our case can be national climate mitigation targets, labels and certificates, incentive schemes and building codes and relevant laws enforced by the authorities. Informal institutions can include a voluntary agreement, social norms and values. Actors in TIS include firms in all parts of the value chain and any organization contributing to the emerging technology (Suurs, 2009). In our case this involves governmental authorities, NGOs, research institutes, developers, design and construction companies, components companies, contractors and clients etc. Networks are an intermediate form of organization between hierarchies (internal organization within entities such as firms) and markets. Their essential function is the exchange of information and it is often informal rather than formal (Carlsson & Stankiewicz, 1991). In addition to Institutions and Actors and Networks we also consider factors that are external to the TIS structure.

INSTITUTIONS

Germany is governed through a strongly federalist system which takes the main responsibility for climate change mitigation, with decentralized powers and resources at the regional (land) and city (stadt) levels that share strong implementation incentives (Power & Zulauf, 2011). The building codes have been strengthened several times over the past 35 years. The first thermal insulation ordinance was in 1977. Since then the German building code (energy saving ordinance EnEV) was introduced in 2002 and amended in 2004, 2007 and 2009. Revisions to EnEV 2009 for 2014 and 2020 are currently discussed and by some expected to approach the PH standard (Schimschar et al., 2011). Germany's building codes, thermal insulation standard for example, were initially not too stringent in the 1970s but have been strengthened considerably over time, especially since mid-1990s (Noailly, 2012). On the local level, many regions and municipalities have applied the passive house standard in new public buildings for several years. The building codes are a combination of prescriptive and performance-based. The country has also revised its Heating Costs Act in 2009 accordingly that motivated residents to save energy by regulating the cost of heating and hot water in rented apartments, which makes up 60 % of total households in Germany (Power & Zulauf, 2011).

Sweden is a unitary state with a history of strong local government involvement in public affairs. The country has also committed to reach the European targets that new buildings should be "near-zero energy" from 2020 and onwards. However, the definition of "near-zero energy" is debated. Today the building code heating requirements of residential and public buildings are 80 kWh/m^2 and 90 kWh/m^2 respectively in southern Sweden. There has been a shift from prescriptive to performance-based building codes since Sweden joined EU in 1995 (Meacham, 2010).The Swedish building codes in the 1970s and 1980s were among the most stringent in the world but are now perceived as relatively lenient. Today the passive house standard is voluntary and there is not much support at the national level for making PH or any other high efficiency standard mandatory.

China's political system in terms of central-regional/local relations is functioning more and more along federalist lines, in which the activities of government are divided between the provinces and the center in such a way that each level of government makes final decisions in certain fields (Zheng, 2009). However, the central government still has a decisive role in sustainability issues, as economic growth is often prioritized in practice locally. Relative to the average energy use level of the buildings in 1980s, the initial residential building codes required 30 % lower energy use in 1986 and 50 % lower in 1995. The current residential building code (for severe cold and cold zones) is now 65 % lower than the 1980 level. This is equivalent to the German building code in the 1990s (MOHURD, 2012). The 2005 standard for public buildings set the target at 50 % energy reduction. At the local level, some cities require 75 % energy reduction relative to 1980 levels in local residential building codes. China's prescriptive-based building codes leaves less space for innovation, as the requirements are given to each building envelope component instead of the integrated system. Recent demonstration projects have used the German passive house standard.

ACTORS AND NETWORKS

Due to different political and economic systems as well as other differences, the actors play different roles in the studied countries. For example, partnerships between public and private seem to be more rooted in Germany and there is also a solid support for SMEs. These aspects are less evident in Sweden and China. In Sweden, local authorities are exercising power in pushing the energy efficiency in new Swedish buildings through procurement specifications and conditioning of land deals. The majority of passive houses are procured or built by municipalities in Sweden. In China the National government has a central role in the PH development. In Germany and Sweden the development is mainly "bottom-up" (albeit in different ways) whereas a "top-down" development still dominates in China. Key actors have been identified as BMVBS (German Federal Ministry of Transport, Building and Urban Development), municipalities, the Passive House Institute and various SMEs in Germany; Municipalities, major construction companies and the Passive House Centre in Sweden; and the Ministry of Housing and Urban-rural Development (MOHURD) in China.

There are various formal and informal networks in both Germany and Sweden through research and demonstration projects, conferences, collaboration networks between municipalities (e.g., Miljöbyggprogram Syd in Sweden), and in the organization of events such as "open house" day. A private initiative, SVEBY (abbreviation for standardise and verify the energy performance of buildings), includes interest organizations, builders, real estate owners, as well as construction companies. SVEBY develops tools and standards for formulating efficiency requirements and for monitoring and evaluation of energy use in buildings. There are also broader network organizations for energy efficiency in general.

As China is still at the preparation phase, technology transfer currently plays an essential role in the innovation system. This is formally supported by networks with Germany, both at governmental and industry levels. The central government has supported the demonstration projects initiated by private developers but this has been on a case-by-case basis and there is no written policy to guide the various actors in China.

EXTERNAL FACTORS

One critique of TIS is that the framework is confined in the internal system, without the consideration of external factors that could be important. These may include the purpose of the technology development, e.g., whether it is export-oriented or driven mainly by environmental concerns. Other influencing factors include, for example, the current and future energy supply structure, its CO_2 emissions, the district heating share, the construction rate in the building sector, or other competing efficiency concepts as noted above in the technology section. These factors may influence the direction of search in the technology adaptation in each country.

First of all, the domestic market formation is not so important if the technology is developed for the purpose of export. Similarly, whether the knowledge is created locally or transferred from abroad does not matter much in the beginning if the main driver is environmental sustainability. Despite the export-oriented nature of the economy in Germany and Sweden the building sector and construction industry is very local and national. Energy efficiency and PHs is mainly motivated by environmental concerns, although Germany, and to some extent Sweden, is starting to explore export opportunities. In China, environmental and energy security concerns motivate the move towards PHs, and in this case we focus on the technology transfer at the preparation stage.

Second, different energy supply structures potentially motivate or hinder the direction of search. Oil and gas are the main sources for residential space heating and hot water in Germany. The district heating share is only about 13.3 % of the total heating market (Ecoheat4eu, 2011). Due to high CO_2 emissions from the building sector, the nuclear phase-out plan by 2022, the increasing electricity prices and the energy import dependency, developing PH technology is strongly motivated in Germany. In Sweden the use of electric heating and heat-pumps, in combination with some other form of heating, e.g. wood or pellets, is common in single family houses. District heating is the most common form of heating in multi-family buildings, accounting for about 86 % of the area being heated (Ericsson, 2009). The high share of renewable energy in electricity and district heat production results in very low CO_2 emission and low dependence on imported fuels in the building sector. Thus, adopting PH technology is motivated more by energy savings and resource efficiency and less by emission reductions and energy security.

In China coal is still the dominant source for energy supply, with a share of 68 % in total primary energy supply (National Bureau of Statistics of China, 2012). Despite the dominance of coal, per capita CO_2 emissions from the building sector is only slightly higher than in Sweden, mainly due to the lack of heating systems in the south of Yangtze River and relatively low indoor comfort levels. District heating covers around 70 % (2006) of the building area in the north of Yangtze River, and nearly 100 % of buildings here are equipped with heating in winter (Tsinghua University Building Energy Efficiency Research Center, 2010). If China were to adopt passive house principles in the northern regions, it can potentially save 14.7 EJ primary energy accumulated over the next 10 years compared with the current building codes. In the cold-winter/warm-summer zone, where 50 % of the buildings are located and district heating is not available, passive house principles could help decrease the electricity use for heating and largely increase the indoor comfort level as the regions has 80 days below 15 °C in winter (Zhang, 2011).

Functional analysis

F1, ENTREPRENEURIAL ACTIVITIES

A widely quoted definition of entrepreneurship is that it is about the "discovery and exploitation of opportunities" (Szirmai, Naude, & Goedhuys, 2011).The entrepreneurial activities involve projects aimed at proving the usefulness of the emerging technology, e.g., through demonstration projects. They depend on and co-evolve with other functions, e.g., Guidance of Search. Entrepreneurs can be both private enterprises and public actors (Suurs, 2009). The passive house concept is an integrated process and system innovation which is based on combining existing knowledge rather than radical change. Entrepreneurial activities are not necessarily undertaken by the actors who created the original innovation. In building sector, developers are the key actors in the supply chain for the delivery of projects and thus they are the main focus of passive house entrepreneurs. Among our cases, Germany has very strong entrepreneurial activities and a tradition of public-private partnership in implementation. Entrepreneurial activities in Sweden are moderate but a rapid grow is seen in the last ten-years. China has just started to take up the concept through pilot projects and this function is still relatively weak.

In 1991, the first pilot project was built in Darmstadt Kranichstein by a private property developer association, following the "Passive House Preparatory Research Project" funded by the State of Hesse (International Passive House Association, n.d.). Since then, many municipalities have supported the development leading to up-scaling and application in different types of buildings through an increasing number of projects. The construction and design companies are still mainly small and medium-sized enterprises (SMEs) and they often enter into public-private partnerships (PPPs). The use of life cycle approaches and consideration of PH principles early in the project process has been common practice over the past ten years (Bähr & Grubbel, 2012). In 2000, the first multi-story passive houses were built in Kassel (Hermelink, 2009) and this further promoted up-scaling as a majority of Germans live in apartments.

In Sweden, the first passive houses were built in Lindås in 2001 as part of the CEPHEUS project, through the cooperation between EFEM Architects, Lund University, Chalmers University of Technology and the SP Technical Research Institute of Sweden (Janson, 2008). The demonstration project considered the energy performance in the very early design phase and showed that it is possible to build passive houses in the Swedish climate. Our interviews show that the development in the past ten years was primarily supported and driven by municipalities in their dual role as developers and regulators. This is contrasted by private developers and investors that have shown less interest at this stage. Major construction companies such as NCC, Skanska and PEAB are already actively involved in the passive houses construction with more than half of market share. Some SMEs are committed to passive houses but sense that they face high risks. In Sweden single-family houses represent 30 % of the total dwellings (Mahapatra et al., 2012). More than half of the new-build of these houses are prefabricated (Finansinspektionen, 2012). However, many of the prefab companies show limited interests in the PH concept or are even against it since it is perceived to challenge their business model.

The first passive house in China, the German pavilion Hamburg house was built for the Shanghai World Expo in 2010. Since then, five demonstration projects in different climate zone, have been proposed and started under a Chinese-German cooperation, i.e., the 2011 Joint Declaration on cooperation in the fields of sustainable mobility, energy efficiency and innovative transport technology. These demonstration projects are mainly "top-down" and initiated or supported by MOHURD. But considering the expected market developments cost reductions from less heating installations, some private developers also show interests in PH. This could increase if a clearer government policy and support scheme was officially put in place. Again, the entrepreneurial activities very much depend on the guidance of search.

F2, KNOWLEDGE DEVELOPMENT

This function refers to the educational and knowledge building conducted by universities and other actors in national and European-wide research projects. Learning-by-doing through design, engineering and craftsmen practices is also included. This function is relatively weak in all three countries, although Germany is stronger in this respect through accumulated experience over the past 20 years. There are many examples of knowledge development and educational efforts, but according to the interviews there is still a general shortage of expertise. Passive house as an integrated system is hardly covered in higher level education where focus still seems to be on single building components.

In Germany, the Passivhaus Institute is the central actor in the innovation system through defining the German passive house standard and its offering of certification as well as courses all over the world. The Fraunhofer Institute for Building Physics, and the Fraunhofer Institute for Solar Energy System are both active in building engineering, design and simulation. Various research institutes contribute to strengthening the innovation system in Germany by bringing together research, industry, politics and society. In Sweden, aside from education program at Lund University, the Swedish Passive House Center provides training courses. The "Lågan" project that started in 2010 supports demonstration projects and promotes local-regional cooperation, as well as provides training for craftsmen. Another important aspect of knowledge development in Sweden is through the monitoring and evaluation of the demonstration projects. Interviewees report that this is an important aspect, especially in the early stages of development. In China there are several universities, and the Chinese Academy of Science, that offer energy efficient design education and research, although not in particular on the PH concept. The hands-on passive house knowledge is gained through vocational training and workshops organized by MOHURD and learning-by-doing from the demonstration projects.

Several EU funded research projects have improved knowledge, but also spread interest and knowledge around Europe. Examples include the Cost Efficient Passive House as European Standards (CEPHEUS, 1998–2000), Promotion of European Passive House (PEP, 2007), as well as the Pass-NET and Pass-REg projects. These projects are not only technology demonstrations. They include creation of conditions for broad market introduction through development of information packages and communication, establishment of passive house databases and sharing of experiences, and more recently by including the onsite renewable energy integration in the passive houses. PHs is not the singular goal and the focus but rather sustainable zero energy buildings, based on passive house principles.

F3, KNOWLEDGE DIFFUSION

As noted, the passive house represents an integrated higher quality product rather than a specific breakthrough energy technology innovation. It took about 15 years in Germany for the PH standard to spread across the country and be adopted as the official standard. Different networks in the three countries connect the government, research and development, industry and building users. Intermediate organizations have played a significant role in this context in Germany (i.e., the PH Institute) and Sweden (i.e., the PH Center) through dissemination of knowledge. A similar active and visible institute has not yet been formed in China. Technology transfer from Germany dominates the development at this early stage with cooperation both at government and industry levels.

The Passivhaus Institute has been a pioneer in diffusing PH knowledge in Germany and worldwide, by organizing conferences and workshops to promote information sharing among governments, researchers, designers, and manufacturers. Several projects that connected Germany and China in recent years have been consulted by the institute. Large-scale projects have an important role in increasing public awareness. In Sweden, the PH center (Passivhuscentrum) is active in diffusing the concept domestically but is also profiling the Västra Götaland region as a forerunner. Nonetheless, there are not yet any significant scale-up projects to spread the concept in the country. The interviews show that such intermediate organizations, although influential, need support and need to be complemented by other mechanisms to further the diffusion process.

Cooperation and knowledge exchange between China and Sweden dates back to the 1980s. Feasibility assessments of passive houses in different climate zones in China were then carried out under a cooperation project between Lund University and the Ministry of Construction in China. But it was difficult to convince the Chinese authorities to build such buildings back then because of the unfamiliar concept and financial constraints (Adamson, 2011). Today the concept is not new, but a leap forward to a passive house standard in China still depends on technology transfer, from abroad and within China, due to the big gap between the PH standard and current building codes. A co-operation with Sweden is on the way to revise the national building codes and the Chinese version of a PH standard. So far, almost all of the demonstration projects have formal or informal cooperation with Germany, which relies on strong networks at both government and industry levels. An official agreement between MOHURD and BMVBS has worked to promote German energy efficient technologies in China and the German Chamber of commerce was involved in the first passive house in Shanghai. The division of EDLE-design architects from Germany has participated in designing the first residential passive house projects in City of Qinghuangdao and a regional PH standard is now developing.

F4, GUIDANCE OF THE SEARCH

The function includes, for example, the climate policy goals, building regulations, other solutions for energy efficient buildings, perceptions of PHs and other aspects that "guide the search" for solutions. This function appears to be quite strong and positive for the PH development in Germany. In Sweden there is no broad consensus on the merits of PHs or the importance of deep energy efficiency in buildings and activities are mainly local. The interest in PHs in China is mainly represented by the central government, although some cities are promoting high levels of energy efficiency.

As noted in the section on institutions, there is a general acceptance and positive attitude towards the PH standard in Germany. This is aligned with the EPBD2 target to reach "near-zero energy" as well as the national target for a climate neutral building stock by 2020. Today several states and cities have implement the passive house standard into the new public buildings (International Passive House Association, 2012). Acceptance and interest from people has been gained through successful examples and financial support.

In Sweden the direction of search at the national level is not clear. But despite the absence of national support, several municipalities show high ambitions in new building projects. The uncertainty concerning future building codes has made the industry hesitate in their commitment and it is difficult for the major construction companies to make long-term plans, according to interviews. The environmental driver is not strong enough, as the building sector in the country is already close to being decarbonized. Compared to Germany, the PH concept is less well known to end users in Sweden. Although the construction industry is generally positive to clear directions in policy and higher energy efficiency requirements, there is also a resistance to adopting a specific PH definition (which gives power to FEBY) rather than having ambitious national building codes.

The direction of search in China is currently in the hands of the central government which provides funding for demonstration projects and follow-up studies. With high urbanization rates and carbon intensive energy supply there are large potentials to reduce emissions through energy efficiency. Improving energy efficiency in buildings is high on the government agenda, and several policies have been implemented, including the heat metering reform, energy labeling, energy efficient appliance promotion and adoption of passive house principles. The current low average emissions per capita are likely to increase as demand for comfort levels increase, not least south of Yangtze River (Zhou, Mcneil and Levine, 2009). However, there are concerns that it will be hard to apply the concept to high-story buildings in China and that the climate conditions in the country are far too complex to adopt a standard based on a Central European climate. Another stated concern is that PH requirements will further increase costs in a housing market where prices are already inflated (this ignores the idea about looking at building life-cycle costs). Studies on how to adapt the PH standard into different climate zones of China are now undertaken.

F5, MARKET FORMATION

This function refers to the market share of passive houses, the type of house, and the financial scheme to support it. The market penetration in Germany is accelerating and a fast grow is also seen in Sweden in recent years. In contrast, no market has formed yet in China where only a small number of demonstration projects have been undertaken so far.

Germany's passive house market penetration has passed the introduction and preparation phases and entered the stage of acceleration. So far, more than 30,000 PH dwellings have been built in Germany (See Figure 1). These are mainly single and two family houses, a building type which accounts for 47 % of dwellings in Germany (Neuhoff, Amecke, Novikova, & Stelmakh, 2011). Geographically, the Frankfurt, Nuremberg and Hanover areas are actively involved in the PH development. Especially Frankfurt is seen as the capital of passive houses. The availability of low interest loans for PHs from the German development bank KfW has been important for the German development.

A recent market survey from the Swedish passive house center (Svensson, 2012) shows that there are more than 2,000 PH dwellings (about 1,900 apartments and 100 single family houses) in Sweden and another 1,300 are in the design and construction phase (see Figure 1). The market share of PH in new construction is increasing and it is now about 3–4 % for multifamily houses and perhaps 0.5 % for single family houses. Nearly all PH apartment buildings are certified according to the FEBY standard and about 75 % of them are built for municipal housing companies. There is no financial support scheme to compensate for the potential extra cost of building a PH although the Swedish Energy Agency can offer some incentives for energy efficient building demonstrations. It should be noted that there is also a large number of un-certified energy efficient buildings that apply PH principles but do not aspire to meet the standard. For example, projects by the companies ByggVesta and Wallenstam were built in this way and reportedly without extra cost. Geographically, the Gothenburg area has been the center of passive house development, followed by Stockholm and Malmö.

China is in the early introduction phase and there is only five projects designed with the German passive house standard. One is located in the severe cold zone, one in the warm-winter/hot-summer zone, and three of them in the cold zone. The demonstration projects started with residential buildings and a few public buildings. Due to the ban on building single family houses in urban areas, all of the proposed projects are multi-family buildings. The central government provides financial support to the demonstration projects but there is no policy that stipulates support levels in place yet.

F6, RESOURCE MOBILIZATION

This function refers to the availability of PH components such as heat exchangers and windows, as well as the knowledge and expertise. The shortage of professionals has been reported as an obstacle in all three countries. Components are generally available in the three countries, but with some exceptions and with limited variety or competition in the market. This may

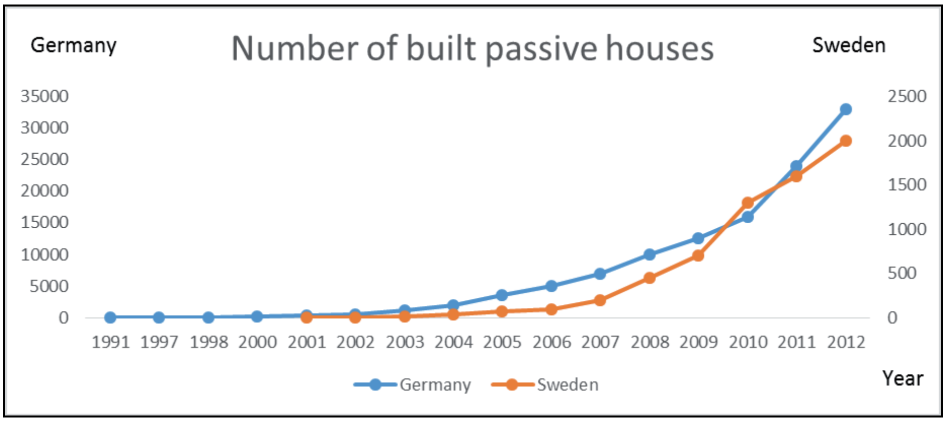

Figure 1. Number of built passive houses in Germany and Sweden (Germany data source: estimated and cited from the PASS-NET project (Lang, 2010), Sweden data source: Svensson, 2012).

constitute a barrier when leading to higher costs, e.g., when necessitating imports.

In Germany the building components are widely available and certified by the Passive House Institute. Components are also manufactured in Sweden but some components are imported from Germany due to a larger variety in the German market. Human resources are reported to be the most challenging factor both in Germany and Sweden. In Germany this is in part due to the general problem of demographic change and a decreasing number of young people graduating from secondary schools (Rammer, 2011). In addition, the number of certified architects and engineers is still relatively small. The possibility to build aesthetically interesting and attractive passive houses has attracted more and more interest from architects in Germany and Sweden. In China, a preliminary survey (Peng, 2011) shows that the main components, except for high performance PH windows, are available in the domestic market. The new residential building code in Beijing (2013) prescribes that the energy use should be 75 % lower than the 1980 level and solar water heating is mandatory. This policy is expected to have considerable impacts on Chinese domestic window manufactures, since very few of them can presently meet the new criteria. Expertise and the technical support for PHs is mainly provided by experts from Germany.

F7, SUPPORT FROM ADVOCACY COALITIONS

According to Sabatier (1998), an advocacy coalition is a policy network of actors, who share similar beliefs and a common policy goal. These actors from different organizations and positions adopt strategies to advance their policy goals through coordination. In Germany, the passive house institute wrote a proposal at the very early stage that calls for attention from the local government. Since then an evolving mix of political and financial support has brought the development up to another level. Enthusiasts have also played an important role. Dr. Wolfgang Feist from the German passive house institute and Hans Eek at Swedish passive house center have both been strong advocates of the PH technology, both regionally and globally. But there is also lobbying against PHs, for example from the prefabricated house industry in Sweden that would potentially lose some competitive advantage from the PH requirements. The advocacy coalitions in Germany and Sweden have worked mainly from the bottom-up, with little support initially from national governments. In China the picture is less clear due to the early stage of development but also due to the less transparent political processes compared to the other countries. One study (Francesch-Huidobro and Mai, 2012) has shown that advocacy coalitions on the climate change issue, for example in Guangdong province, have formed in a top-down manner rather than bottom-up. In the Chinese context it is reasonable to assume that a similar top-down supported process is needed for building support or coalitions for PHs and other high efficiency concepts. To be successful, these concepts must also be aligned with the overall goal of economic development in China. As in other countries, the building sector is a tight regime with strong networks among actors and a shift in building practices is unlikely if it fundamentally challenges the regime and the economic interests of dominant actors.

Summary results and concluding discussion

In Figure 2 we summarize the results of the functional analysis by assigning a value (ranging from absent to very strong) to each function for the three countries. The numbers essentially represent our informed judgment based on the function oriented evaluation of various documents, data and interviews. Figure 2 indicates in which areas that functions are absent/present or weak/strong, providing an overview of system inducement or problems in order to support or hinder the development of the passive house innovation system. However, functional analysis alone is not sufficient. Coupling structure and functions allows us to identify desirable changes in structure and discuss policy implications (Wieczorek & Hekkert, 2012). In this section we focus on: (1) overall functional analysis results and their interactions, at the different development stages of the cases; (2) linking the function and structure, and discuss the policy implication and instruments through innovation structure change by countries; and (3) the usefulness of TIS for policy analysis and development.

FUNCTIONAL ANALYSIS RESULTS AND THEIR INTERACTIONS

As Figure 3 shows, at the introduction stage, knowledge development is the most critical system function (Luo et al., 2012). This has been seen in both Germany and Sweden, where

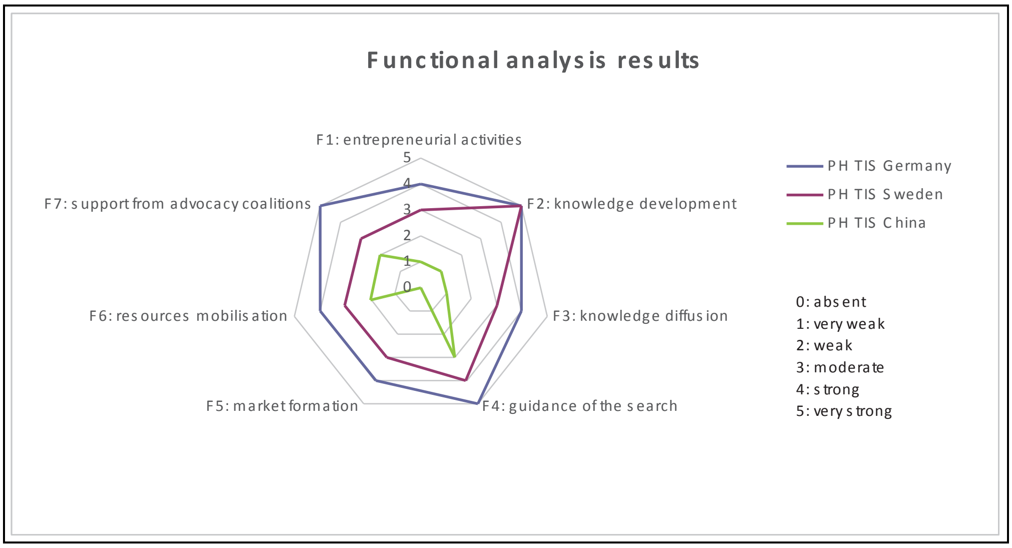

Figure 2. Functional analysis results.

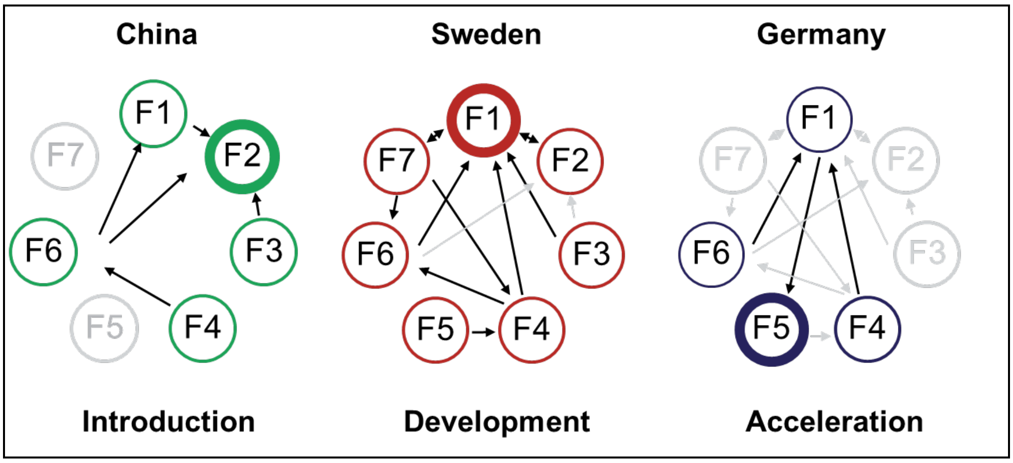

Figure 3. Functional patterns per phase (adapted from TIS Manual (Luo et al., 2012)).

knowledge was developed long before the first PH demonstration projects and this function is very strong in both countries. In the case of China, where technology is transferred instead of developed domestically, knowledge transfer can support the other functions in the short term, particularly knowledge diffusion, but domestic knowledge development is important in the long term. Learning-by-doing will most likely continue to benefit the incremental innovation process in the case of PHs. Using passive house principles is different from other more radical innovations where learning-by-doing may play a less important role.

At the early development stage, entrepreneurial activities are important. They rely strongly on the guidance of search and interacts with the subsequent resource mobilization. This is seen in all the countries through demonstration projects, although projects in Germany may have had a greater impact on the guidance of search and public acceptance through their large scale. In turn, advocacy coalitions and resource mobilization may support or hinder the guidance of search and influence the entrepreneurial activities. This is found in Sweden where lobbies and external factors cause hesitation at the national level.

At the acceleration stage, market formation becomes a greater focus of the innovation system. In Germany and Sweden it took 10–12 and 5–6 years, respectively, before growth took off. While the guidance of search is relatively solid in Germany, resource mobilization aspects such as insufficient expertise could still hamper the further scale-up, despite the traditionally strong ties tradition between industry and research institutes. This indicates the dynamic role of learning through the whole process and the importance of taking it into account at the introduction stage to avoid market lock-in later.

Figure 3 illustrates the current role of different functions in the three countries and indicates the stage of development. Knowledge development, supported by and interacting with other functions is important in China. Entrepreneurial activities are still important in Sweden although Sweden is close behind Germany where market formation is a key function. Our results are qualitative and the complexity is not easily visualized. Figures 2 and 3 are thus intended only as rough visual overviews and guides to our discussion.

COUNTRY-BASED POLICY IMPLICATION

Institution, actors and network have been strengthened in the German PH innovation system over the last 20 years. Institution build-up is a result of the combination of strong advocacy coalitions, knowledge accumulation and external factors such as existing and future energy challenges. A voluntary standard has moved to become semi-official in some locations about 15 years after the first demonstration project. As the early innovator, the German passive house innovation system benefited consistently from the intermediary organizations such as the Passive House Institute through knowledge development and diffusion. The government also played an important role at the growth stage, by introducing low interest loans specifically for passive houses and supporting SMEs, resulting in a variety of entrepreneurial activities. However, the role of educational establishments seems less strong in Germany, and resource mobilization could potentially be enhanced by stronger efforts in education. A combined approach is found in Germany with both strong federal and state or local government. Networking is not least expressed among industry, intermediary organization and research institutes. It is an important part of the innovation process, i.e., formal and informal interaction during the whole project process among developers, architects, engineers, construction craftsmen and other stakeholders. In this way a learning-by-doing process is ensured and the principal-agent problem mitigated, as the purpose of considering energy efficient principles early in the design process is to avoid costly add-on solutions later.

Sweden has seen a fast growing pace of PH share in new buildings in the last five years, despite the absence of national guidance and a nearly de-carbonized building sector. Institutionally, PHs is still a voluntary standard, mainly pushed by a few specific actors, i.e., some municipal governments and construction companies. The dilemma of guidance of search could largely be explained by the external factors, but also lie in the lack of consensus and shared vision between actors at different levels and interests. Negative advocacy coalitions and a proposal to remove the possibility for municipalities to require higher efficiency than building codes stipulate may hinder the search process. Knowledge diffusion could be strengthened by more coordination from intermediary organizations, or scale-up demonstration projects, in order to embrace more private investors and SMEs in the innovation system. Similar to Germany, an early involvement of different stakeholders during the planning process is also found in Sweden.

Since the first demonstration project in China was just finished in January 2013 there is really no innovation system to talk about yet. The functional weakness at this stage is particularly found in knowledge development through technology transfer and learning-by-doing. Entrepreneurial activities have already taken place but are still seeking for a clear guidance. Institutionally, China is still slowly taking up this approach in its design of building codes. Given that the PH standard is quite far away from current building codes, the change is most likely to happen slowly and in a phased approach. Nevertheless, a voluntary PH standard at this stage could be important to provide direction for the industry and facilitate future more ambitious mandatory building codes. The planned demonstration projects, located at different climate zones, mainly involve local governments and private investors, coordinated by central government and German partners. In a Chinese context it can be seen as a top-down approach although it is practiced at the local level. This could create considerable scale-effects to speed up knowledge diffusion. The process could be expected to go even faster in China than other countries if advocacy coalitions are formed and a formalized policy to support demonstration projects and beyond gets established. Considering the magnitude of the social and environmental challenges in China, the question is not whether or not to take action, but how fast it is possible to change policies and practices in China. In the Chinese context we expect a different dynamic between top-down and bottom-up initiatives than in Germany and Sweden. It seems important at this time to also support bottom-up and local initiatives.

THE USE OF TIS FOR POLICY ANALYSIS AND DEVELOPMENT

The application of TIS to understand the different innovation systems has proven to work both in developed countries and in China, although the function focus may be different in different contexts, specifically, including technology transfer is important in developing countries. Although we used PHs as an example to simplify and delimit our analysis, the TIS approach is also likely to be useful for analyzing building energy efficiency in general. Compared to TIS analyses in other areas, including external factors appears as particularly important in our case. The comparative study is designed to understand the innovation diffusion process in different countries, and it also helps understand the mechanisms behind the events at different market penetration stages. TIS appears as a very useful tool for analyzing and developing policy strategies for this type of long term transformational change of the building sector. Our analysis reveals large contextual differences between the three countries, for example, concerning administrative and industrial structures. This implies that direct policy transfer is not likely to be a successful strategy. As discussed above, the innovation systems in Germany and Sweden can be fine-tuned and strengthened in different ways. For China, our analysis shows the importance of thinking beyond single functions (e.g., focusing on building codes). Several functions and their interplay are important for making the transition to high energy efficiency in buildings and a TIS approach with function analysis help reveal strengths and weaknesses in the system. The analysis also shows how the relative importance of different functions changes over time. Thus, a policy strategy should be flexible and adapted depending on the development stage, e.g., different actors moving focus from knowledge formation and entrepreneurs in early phases to market formation and resource mobilization in later phases for a structural change.

Conclusion

The TIS approach was used here to study the dynamics of the passive house diffusion process in Germany, Sweden and China with the aim of extracting knowledge that is relevant to policy strategies for building energy efficiency. It is also the first example of applying this approach to building energy efficiency in a developing country. General insights include (a) the importance of well-functioning innovation systems for making the transition to high energy efficiency in buildings, (b) that bottom-up and top-down initiatives can interact in different ways to reach the same goal, and (c) the importance of adapting a transition strategy to a range of national and local conditions. More specifically, the PH case in Germany and Sweden shows the importance of intermediary organisations in knowledge development and diffusion, and other innovation system functions. Guidance of search, not least expressed through building codes or other requirements, seems particularly important in the case of energy efficiency in buildings and passive houses. This underlines the role of government at different levels. The development of technology innovation systems and technology diffusion are relatively slow processes. In the case of passive houses it took about 20 years in Germany and perhaps 10 years in Sweden, that could learn from the German experience. This indicates that China could potentially make a relative rapid shift in building energy efficiency through learning-by-doing and technology transfer from abroad as well as within China. Specific recommendations for a Chinese policy strategy would require a more detailed analysis of the Chinese situation, but the TIS-approach is a useful and potentially important tool for developing a broader Chinese transition strategy for building energy efficiency. Such a policy strategy should go beyond formulating building codes and demonstration projects, and seriously consider how the innovation system can be strengthened in all its important functions at different stages.

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