Lock-in of mature innovation systems, The transformation toward clean concrete in the Netherlands

Joeri H. Wesseling (joeri.wesseling@circle.lu.se)
CIRCLE, Lund University, Sweden
Alexander van der Vooren (Alexander.vanderVooren@pbl.nl)
Sustainable Development Department, PBL, The Netherlands

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Centre for Innovation, Research and Competence in the Learning Economy (CIRCLE)
Lund University
P.O. Box 117, Sölvegatan 16, S-221 00 Lund, SWEDEN
http://www.circle.lu.se/publications

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Abstract Keywords: system failures; system functions; vested interest; sectoral innovation system; sectoral system of innovation and production; technological innovation system

JEL: O25; O31; O33; O38; Q01

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Joeri H. Wesseling[1] and Alexander van der Vooren[2]

[1]*Centre for Innovation, Research and Competence in the Learning Economy (CIRCLE), Lund University, P.O. Box 117, SE-221 00, Lund, Sweden.* *Joeri.wesseling@circle.lu.se*

[2]*PBL Netherlands Environmental Assessment Agency, Sustainable Development department, PO box 303, 3720AH, Bilthoven, the Netherlands.* *Alexander.vanderVooren@pbl.nl*

Abstract

Energy-intensive processing industries like the concrete industry form the base of the economy and account for a large part of greenhouse gas emissions. Sectoral transformation to cleaner basic materials is therefore crucial, and institutional pressure to do so is increasing. These sectors have nevertheless been largely omitted by socio-technical studies. This paper therefore sets out to analyze the systemic problems that inhibit the transformation of the mature innovation system of the concrete sector toward the development, diffusion and adoption of clean concrete innovations, for the case of the Netherlands. A coupled structural-functional approach has been frequently applied to identify such systemic problems, but has been limited to emerging technological innovation systems. Consequently, the approach tends to overlook the systemic lock-in that arises from interdependent systemic problems and vested interests that characterize mature innovation systems. This paper analyzes these characteristics to extend the application of the structural-functional approach to the transformation of mature innovation systems. Interviews with 28 stakeholders were conducted and triangulated with reports, websites and other documents. A list of systemic problems was identified that originate within actors, institutions, networks, technology and infrastructure and that impaired the performance of all system functions except knowledge development. Systemic problems are indeed found to be strongly interdependent, leading to systemic lock-in. Through strategic, often collective action, established firms with vested interests were able to reinforce these systemic problems to inhibit clean concrete innovation. The study concludes that systemic lock-in inhibits the sustainability transformation of the mature innovation system of concrete in the Netherlands and confirms that the application of the structural-functional approach can be extended from emerging to mature innovation systems.

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1. Introduction

The innovation systems and transitions literature has been valuable in understanding the complex processes that affect the success of emerging, clean technologies and in providing policy recommendations to support the development and diffusion of these technologies. Energy-intensive processing industries have, however, received little attention in this literature, even though they form the base of the economy, are responsible for a large share of GHG emissions (Åhman et al., 2012; Wesseling et al., forthcoming) and are characterized by unique patterns of innovation (Pavitt, 1984). The concrete industry, ranging from the mining and processing of resources to construction, demolition, and recycling of end-products, is a typical example of such an industry. Cement is the most energy-intensive component in concrete and is estimated to account for 5-8% of global CO_2 emissions (Dewald and Achternbosch, 2015; van Oss and Padovani, 2003). To meet long-term emission targets, clean concrete innovations (CCI) are needed throughout the whole supply chain (Allwood et al., 2010; Dewald and Achternbosch, 2015; Hasanbeigi, 2013; van Lieshout, 2015). However, like in other energy-intensive industries, the developed clean innovations typically do not diffuse well in the concrete industry and therefore require closer attention from a socio-technical systems perspective (Dewald and Achternbosch, 2015), which is the goal of this paper.

The coupled structural-functional approach is useful for this purpose, as it enables the identification of systemic problems that inhibit the functioning of innovation systems, which is to develop, diffuse and utilize innovation (Carlsson and Stankiewicz, 1991; Chaminade and Edquist, 2010; Negro et al., 2012) so that user needs can be met under changing conditions (Malerba, 2004). The structural-functional approach has been predominantly applied to emerging technological innovation systems (TIS) (Bergek et al., 2008; Coenen and López, 2010; Hekkert and Negro, 2009), but this paper argues it is also applicable to study the transformation of mature sectoral systems of innovation and production (SSI) like that of the concrete industry. Over at least the past century this sector has settled around mature technologies[1], an established supply chain and infrastructure, has obtained a dominant market share in construction materials and has become strongly institutionalized (Dewald and Achternbosch, 2015). The societal challenge of climate change is increasingly pressuring this system to transform toward the development, diffusion and utilization of CCI.

Extending the application of the structural-functional approach to the transformation of sectorally-delineated, mature innovation systems however demands attention to how its characteristics differ from emerging TIS. Firstly, mature SSI may encompass multiple technologies or products that compete on a (segmented) mass market. Secondly, mature systems are characterized by strong interactions between innovation system components (Bergek et al., 2008) that lead to interdependent systemic problems (Carlsson and Jacobsson, 1997; Kieft et al., 2016; Negro et al., 2012) that may result in systemic lock-in. Third, vested interests are expected to affect the transformation of energy-intensive industries, like the concrete industry toward clean innovation (Dewald and Achternbosch, 2015; Wesseling et al., forthcoming). The current study complements the coupled structural-functional approach with a critical analysis of these, so far, overlooked characteristics (Kieft et al., 2016; Negro et al., 2012), to extend its application to the transformation of mature SSI.

[1] Concrete's prime ingredient cement for example has relied for the past 190 years on the dominant design of Ordinary Portland Cement (Worrell et al., 2001).

The contributions of this paper are thus twofold. First, it extends the application of the structural-functional approach to mature SSI to analyze the systemic lock-in that inhibits the sectoral transformation toward CCI. In the light of this special volume, this study shows how vested interests differ along the supply chain and how these add to the systemic lock-in. Second, it provides insights into the transformational dynamics of an energy-intensive processing industry, which have received little attention from transitions studies. Based on the results, policy recommendations are provided to support CCI.

This study focuses on the case of the Netherlands. The Netherlands produces 14-15 million cubic meters of concrete per year (Cement&Beton, 2016), which accounts for 1.8% of national CO_2 emissions and demands 1.1% of national energy use (Bijleveld et al., 2013). These numbers are low compared to the world average, because the construction sector attributes only a small portion of our GDP (due to prosperity), Dutch concrete production is relatively clean and its most polluting component, cement, is mostly imported from nearby countries (Bijleveld et al., 2013). To illustrate, the only cement producer in the Netherlands (ENCI B.V.) is owned by multinational HeidelbergCement and will close in 2018.

The subsequent Theory section first justifies the use of the innovation system perspective and then discusses innovation system delineation, transformation, lock-in and finally the use of the system functions approach to study the transformation of SSI instead SSI's conventional approach. Section 3 describes the methods. Section 4 first provides an overview of the concrete industry's supply chain and relevant CCI, then discusses the systemic problems structured according to the system functions they affect, and finally describes the interdependencies of the systemic problems. Conclusions and policy recommendations are provided in Section 5.

2. Theory

Within transition studies, the multi-level perspective studies broad sectors that have significant societal impact, like energy, construction and transport (Geels, 2004). The subsectors that supply substitutable inputs to these broader socio-technical regimes (such as concrete for construction) have, however, less societal impact when they transform. To illustrate, the partial replacement of cement with geopolymers in concrete may bring about a significant transformation of the concrete sector, but will have limited impact on the broader construction regime. The innovation systems perspective is therefore more appropriate to study such subsectors (Dewald and Achternbosch, 2015).

2.1 Innovation system delineation

Innovation systems are defined by their structural components, i.e. the actors[2], networks, institutions and technology[3] that contribute to the development, diffusion and utilization of innovation. Innovation systems have been delineated by national, sectoral, regional, and technological boundaries. Identifying a product-type-specific innovation system, like that of concrete, as a TIS or a sectoral system of innovation and production (SSI) is complicated by the fact that 1) both types of systems can be defined by products, and 2) system delineation is often

[2] Including for example industry, users, policy makers, research institutes and intermediary organizations
[3] Sometimes referred to as materiality

perceived as a research-question driven, pragmatic and therefore flexible step (Bergek et al., 2015; Malerba, 2002; Markard et al., 2015).

To illustrate, a TIS can be defined along a specific technical knowledge field or along a "product and its applications" (Bergek et al., 2015, p.52; Markard and Truffer, 2008; Markard et al., 2015). TIS are embedded in sectoral contexts, like construction, or subsectoral contexts like concrete, plastics and steel. SSI, defined as "a set of new and established products for specific uses and the set of agents carrying out interactions for the creation, production and sale of those products" (Malerba, 2002, p.261), can be delineated at any of these sectoral levels. Within these subsectors, different TIS may be identified at the product level (e.g. electric cars), the component level (e.g. batteries) or the knowledge field (e.g. electric mobility) (Markard et al., 2015, p.78). TIS may span sectors when they include the whole value chain of a product or technology (Bergek et al., 2015) and both TIS and SSI may span the national boundaries of innovation systems (NIS), see Figure 1. When a TIS dominates an SSI, their boundaries may coincide.

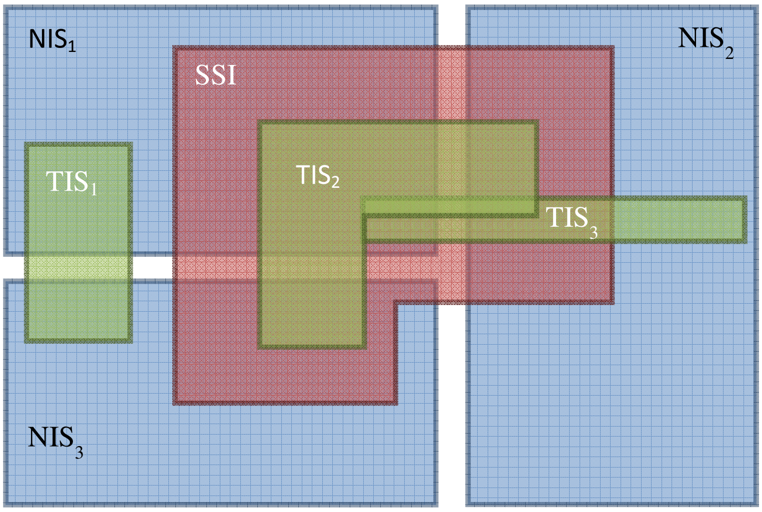

Figure 1, Relations between innovation system boundaries, adapted from Hekkert et al., 2007.

2.2 Innovation system transformation

Since the 2000s, TIS studies have typically focused on emerging innovation systems in the formative phase and neglect mature systems (Hansen and Coenen, 2015) or relegate them to the emerging system's context (Bergek et al., 2015). Because SSI may include both new and established products (Malerba, 2002), they may encompass both mature TIS that are well-entrenched in the SSI (Figure 1, TIS_2) and emerging TIS that are less aligned with the SSI (Figure 1, TIS_3). While emerging TIS are concerned with system growth, mature SSI are more concerned about system transformation; both involve changes in the structural components of the system. These components constitute systemic problems[4] when they inhibit system functioning, meaning system growth for emerging TIS but which we interpret as directional system transformation for mature SSI[5].

In the context of system transformation, SSI transformation involves the development, diffusion and utilization of innovations (and the system components that support this), directed along a new pathway such as sustainability. The "radicality" of such innovations may be approached by "the degree of change along the value chain (vertical novelty) and the degree of change in a single element of the value chain (horizontal novelty)" (Markard and Truffer, 2006, p.613). The more radical technological innovations can be conceptualized as emerging TIS and will induce a larger change in the structural components of the SSI when they replace established TIS. A transformation of the automobile sector, for example toward hydrogen fuel cell vehicles, involves radical drivetrain and value chain changes and will thus be more significant than the transformation toward the less radical hybrid electric vehicles (Hekkert et al., 2005).

With respect to the case at hand, this paper interprets the innovation system of concrete as a mature SSI that is undergoing a period of sustainability transformation toward the development, diffusion and utilization of CCI. These CCI constitute technical and process innovations with different degrees of horizontal and vertical novelty that each affect different parts of the supply chain of concrete. The more radical technical CCI can be perceived as emerging TIS that aim to grow at the cost of the established technologies.

2.3 Innovation system lock-in

As innovation systems mature, their industry population stabilizes and firms become established (Utterback and Suarez, 1993), networks solidify, institutionalization takes place, infrastructure optimizes and technological trajectories become set. Hence, the system's structural components align and become more interdependent (Malerba, 2002; Bergek et al., 2015), resulting in path-dependencies (Carlsson and Jacobsson, 1997). Radical innovations that overthrow this stability typically run into systemic problems formed by the structural components that are unable or unwilling to facilitate radical innovation. The interdependence of these structural components are expected to lead to interdependent systemic problems (Kieft et al., 2016; Negro et al., 2012), which inhibit transformation of the SSI and may result in a state of systemic lock-in (Carlsson and Jacobsson, 1997, p.303). Turner et al. (2016) show this for the agricultural sector, while Negro et al. (2012) provide the example of policy that inhibits innovation, but which cannot be improved due to misinformed policy-makers and the inability of entrepreneurs to inform them. Interdependencies may also arise along the value chain, for example when manufacturers cannot innovate because the suppliers on which they depend have no incentive to deliver the necessary inputs. To understand and overcome the inability of an SSI to transform requires the untangling and coherent solving of the interdependent systemic problems that comprise systemic lock- in.

Mature SSI are typically dominated by established firms that have vested interests in maintaining the status quo and that may oppose pioneers of radical innovation. To protect their profitable position,

[4] These systemic problems (Negro et al., 2012) have also been labeled system failures (Klein Woolthuis et al., 2005), systemic imperfections (van Mierlo et al., 2010), and blocking mechanisms (Bergek et al., 2008).

[5] Analyzing sectoral transformation therefore enables the identification of both, what Weber and Rohracher (201) label, structural and transformational system failures.

which is often technology-specific (Teece et al., 1997), and to deter new entrants, established firms have been found to strategically inhibit or steer processes of socio-technical change (Penna and Geels, 2015; Smink et al., 2015; Wesseling et al., 2015). The incentive to strategically influence innovation differs between firms and particularly along the supply chain of a product, as innovations affect the links of the supply chain differently. Such agency remains insufficiently studied in the innovation systems literature (Farla et al., 2012).

In conclusion, when studying the transformation of mature innovation systems it is important to incorporate the interdependence of systemic problems and the role of vested interests into the analysis. These factors have been identified as valuable venues to further innovation systems research (Bergek et al., 2015, 2008; Kieft et al., 2016; Markard et al., 2015; Raven et al., 2015).

2.4 Assessing innovation system functioning

SSI and TIS typically employ different approaches to assess the function of innovation systems. The SSI literature analyzes system transformation through the interplay of structural components or "building blocks" to identify systemic problems (Faber and Hoppe, 2013; Malerba, 2002; Oltra and Saint Jean, 2009). The TIS literature however argues that an analysis of structural components alone cannot assess where systemic problems lie, because it does not systematically incorporate how these problems affect the processes that are key to successful innovation. For this purpose the system functions approach has been developed (Bergek et al., 2008; Hekkert et al., 2007). System functions capture processes that are key to innovation and constitute the "intermediate variables between structure and system performance" (Jacobsson and Bergek, 2011, p.46). Table 1 provides an overview and description of the system functions used in this paper. These system functions are interdependent and cycles of positive feedback constitute system development, which can be blocked when some system functions are impaired or develop negatively (Suurs and Hekkert, 2009).

Table 1, Overview of system functions and their description, based on Hekkert et al. (2007).

System functions	Description
Entrepreneurial activities	Entrepreneurial experimentation and commercialization of innovations (e.g. pilots)
Knowledge development	Learning by searching and by doing (e.g. R&D)
Knowledge diffusion	Exchange of tacit and codified knowledge in formal and informal networks; learning by interacting and by using
Guidance of the search	(In)direct selection of technological trajectories (in SIS) or designs (in TIS) in transformation or development processes
Market formation	Creation of protected niches (through regulations, policy and standards) and subsequently mass market demand
Resources mobilization	Allocation of financial, human and other resources to fulfill other system functions
Creation of legitimacy	Create legitimacy for a technological trajectory; includes lobbying

The underdeveloped system functions identified by the functions approach can only be meaningfully understood and influenced by relating them back to the structural components that caused them, i.e. the systemic problems (Jacobsson and Bergek, 2011). Likewise, Wieczorek and Hekkert (2012, p.78) argue that "functions cannot be influenced without altering a structural element". Systemic problems might occur because structural elements are missing, do not support or even oppose the functioning, growth or transformation of an innovation system. The innovation system literature is abundant with classifications of systemic problems[6]. Recognizing this diversity and complexity, we adhere to Wieczorek and Hekkert's (2012) classification of systemic problems along the structural components of an innovation system. Hence, a coupled functional-structural analysis allows for identifying and understanding the systemic drivers and problems to innovation, which is necessary in order to draft effective policy interventions (Jacobsson and Bergek, 2011; Wieczorek and Hekkert, 2012).

Although the system functions approach has been applied predominantly to emerging TIS to assess system growth, it can be applied more broadly (Bergek et al., 2008; Coenen and Lopez, 2010; Galli and Teubel, 1997). System functions studies have extensively analyzed the agriculture sector (Kebebe et al., 2015; Lamprinopoulou et al., 2014; Turner et al., 2016) and some studies interpret sectors as TIS instead of as SSI, such as the Finnish life sciences industry (Patana et al., 2013). Instead of applying the typical SSI building blocks approach (Malerba, 2002), this paper applies the system functions approach to study the transformation of a mature SSI because it provides better insight into how systemic problems affect the interdependencies of specific innovation processes (Bergek et al., 2008; Hekkert et al., 2007).

3. Methods

To explore the systemic problems that inhibit the commercialization of CCI for the case of the Netherlands, we adopt a structural-functional approach that is characterized by several analytical steps (Bergek et al., 2008; Wieczorek and Hekkert, 2012). We adopt these steps and add the fourth step to identify interdependencies between systemic problems as suggested by Kieft et al. (2016), as this enables us to also study more deeply embedded problems and the role of established firms' vested interests. The analytical steps taken in this paper include:

1. Preliminary mapping out the SIS' structural components
2. Functional analysis to assess functional performance
3. Identification of systemic problems in the structural components that inhibit functional performance
4. Identification of interdependencies between systemic problems to detect more deeply embedded problems
5. Formulation of policy measures to alleviate potentially interdependent systemic problems

To assess the performance of the system functions depicted in Table 1, we used the established operationalization scheme in various TIS studies (e.g. Hekkert and Negro, 2009; Negro et al., 2007; Suurs and Hekkert, 2009; Wieczorek and Hekkert, 2012) that attributes indicators to this set of functions.

Data were obtained from 26 semi-structured, in-depth interviews with 28 stakeholders, conducted by the PBL Netherlands Environmental Assessment Agency. Stakeholders included each type of firm along the supply chain of concrete, encompassing small and large established firms (15), many of

[6] See for example Chaminade and Edquist (2010); Jacobsson and Johnson (2000); Klein-Woolthuis et al. (2005); Negro et al. (2012); Weber and Rohracher (2012); Wieczorek and Hekkert (2012)

which participated in norm and certification committees, as well as new entrants (3); public agencies which issue policy and are the most important buyer of concrete (3); industry associations (6); and an independent expert in the field. A list of interviewees can be found in the PBL report (van der Vooren et al., 2015). Interviews were conducted from January 2014 to June 2015, recorded on digital media and subsequently transcribed in an integrated way. These transcripts were coded for analysis using the seven system functions. Through these system functions, systemic problems were identified in the structural components of the innovation system. After describing these problematic components, the interdependencies between them were identified. Seventeen stakeholders[7] verified and commented on the draft of the PBL report that was sent around; this resulted in incremental improvements. To facilitate candid responses on the sensitive topic of study, the interviewees were granted anonymity. To enhance transparency of the references in the Analysis section, each actor type was attributed a corresponding reference code: EF for established firms including incumbents; NE for new entrants; IA for industry associations; PM for policy makers and the independent expert. The numbers to specify each interviewee within each code were randomized.

To prepare the semi-structured interviews, information was obtained from newspaper articles, annual reports, websites, government documents and position papers. As far as possible, these documents were also used for triangulation of the interview data.

4. Results

In this section we first map out the supply chain of concrete and its various clean innovations. Subsequently, we discuss the coupled structural-functional analysis to identify systemic problems, followed by an analysis of the interdependencies of these problems.

4.1 Concrete supply chain and clean innovations

Concrete is produced from a mixture of cement with sand, gravel and water. In the Netherlands, cement is partially replaced by additive materials with binding properties, such as blast furnace slag and coal fly ash, while sand and gravel can be replaced by granulated recycled concrete. Utilization of locally available alternative binders and secondary fuels makes Dutch concrete particularly clean. The supply chain is depicted in Figure 2. Companies differ strongly in their level of vertical integration along the supply chain; there are firms that are active in mining, cement mixing and mortar production, but also firms that specialize in one activity. Business cases also differ along the supply chain; cement companies, for example, want to sell as much cement as possible, while mortar companies want to reduce the share of cement to reduce their cost price. Vested interests differ accordingly, causing firms to have different outlooks on the types of CCI. Overall, the concrete SSI is characterized by product and process innovations aimed at incremental cost reduction through resource and energy efficiency.

[7] Five out of seventeen are from the list of interviewees.

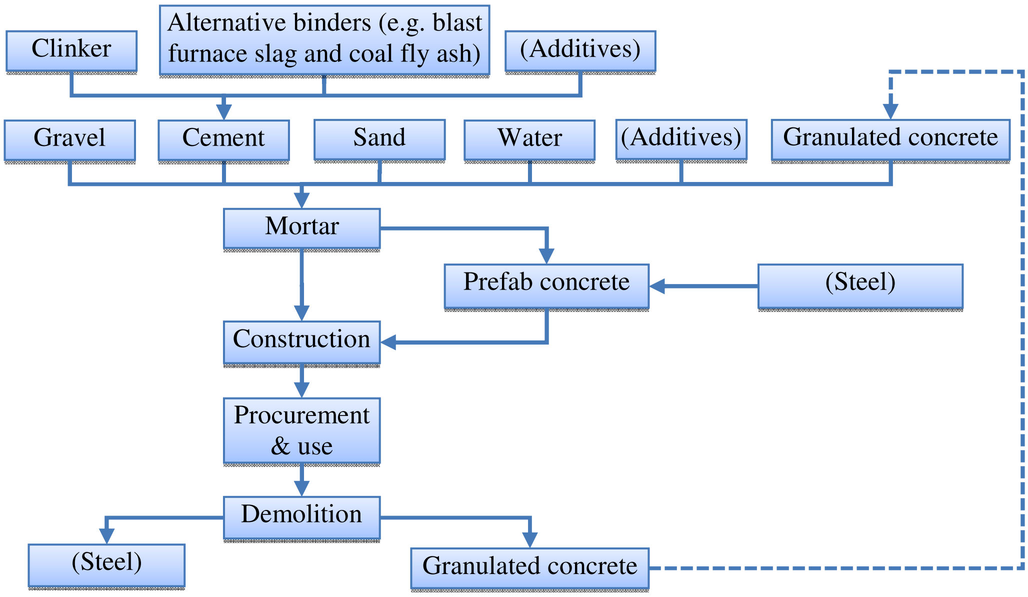

Figure 2, Overview of the supply chain of concrete, adapted from Bijleveld et al. (2013).

There are different CCI that can contribute to the sustainability transformation of the concrete SSI. Table 2 lists the CCI that were selected as promising in a study by CE Delft in cooperation with industry players (van Lieshout, 2015), a process that interviewees (EF4/12/13; P4) described as highly political. Many CCI are complementary in nature as it is possible to combine the categories in Table 2. These innovations differ in their radicality; some are more technically advanced, such as geopolymers, whereas others like recycled granulated concrete have a larger impact on the supply chain. In the following analysis, we will identify systemic problems related to the development and diffusion of these and other CCI, to subsequently analyze the interdependence of these problems.

Category	Specific CCI
Changes in concrete composition	Optimize grain distribution
	Expand the resources allowed for making cement (CEM X)
	Use calcium sulfoaluminate cements (CSA)
	Use super sulphated cements
	Use alternative CSH cement
	Use geopolymers as cement
Reuse/recycling	Build with demountable standard units
	Cement recycling via smart demolition and/or ADR (mechanical)
	Thermal cement recycling
	Use of bottom ash as filler with binding capacity
Other reinforcement methods	Use of steel fiber instead of traditional reinforcement in cast concrete
Adjust construction process	Longer solidification time cast concrete by adjusting construction planning
	Reduce oversizing in design phase
Increase lifetime	Longer lifetime through flexible design
	Self-healing concrete
Energy demand in user phase	Concrete-core-activation in combination with heat pump and geothermal heating as addition to the energy-performance-norm

Table 2, Overview of the 16 most promising CCI, as perceived by the Green Deal but excluding important innovations like alternative construction materials and carbon capture and storage, source: van Lieshout (2015).

4.2 Identification of systemic problems

Structured along the system functions of Hekkert et al. (2007), we present the results of the coupled structural-functional analysis that led to the identification of various systemic problems. At the end of this subsection, Table 3 provides an overview of the systemic problems that inhibit the development and diffusion of CCI.

Entrepreneurial activities

As Table 2 indicates, the Dutch concrete industry is experimenting with different CCI. Established firms dominate this industry. Fifteen interviewees[8] indicated that the incentive of established firms to experiment with and commercialize CCI depends on their activities in the supply chain. They indicated for example that innovations that replace or reduce conventional concrete inputs (see first set of rows, Table 2) receive opposition from cement, sand and gravel companies but are supported by mortar and prefab companies because reducing input resources, particularly cement, may lower their cost price. Concrete recycling companies do not necessarily benefit from reusing or recycling innovations (second set of rows) because these innovations impose a lot of extra restrictions on the demolition process and currently they can still use granulate concrete as fundaments for roads. Finally, interviewees (EF2/7/10/12; IA2/5) argued that organizational innovations that reduce mortar sales by preventing oversizing in the design phase disadvantage mortar companies who want to sell as much mortar as possible, but benefits prefab companies who can use less mortar in their product and lower their cost price. Hence, different vested interests along the supply chain reduce entrepreneurial activities in the field of CCI.

The concrete industry has high barriers to entry due to its high capital-intensity of operation and innovation, high market concentration, strong buyer-supplier ties and varying levels of vertical integration (EF3/4/7/9; Vermeulen et al., 2007). Despite the entry barriers, there have been several new entrants that have introduced new cements, admixtures or competing materials. For their commercial success, these new entrants are dependent on incumbents for their resources and networks. Often they enter the low-end and prefab market segments because they are more open to entrepreneurial experimentation as they are less regulated, less certificate-intensive and enable modular construction[9] (NE1/3; EF10/13). Interviewees (NE1/3; EF1/4/13; P2) indicated that in mainstream markets (such as buildings and infrastructure) conservative regulations, norms and certificates demand so much time, capital and influence that only incumbent firms can comply and/or change these institutions to engage in experimentation and commercialization of innovations.

Knowledge development

Knowledge development in the concrete industry is often demand-driven (Aitcin, 2000). Learning by experimentation is important and frequently used by firms to develop CCI, but is hampered by the

[8] I.e. interviewees (NE1; EF1/2/4/6-8/10/12/13; IA2/3/5; P2/3)

[9] Poured concrete that forms the basis of a structure cannot be taken out, whereas prefabricated products are modular and can be replaced more easily.

long lifetime of concrete; more expensive testing facilities that approach these long lifetimes by imitating decades of decay are not accessible to every firm. Material analytics is identified as a possible tool to speed-up learning by experimentation (Dewald and Achternbosch, 2015).

Multinational cement incumbents like HeidelbergCement and Lafarge are very active in knowledge development, as they invest significantly in R&D[10] , but the share of R&D for CCI is unknown. Although established firms may explore CCI through R&D, some of them indicated that they are reluctant to commercially pioneer innovations that would undermine their own profitable position (EF5-7/12/13; IA3). Due to their lack of capital, smaller firms engage much less in R&D (EF8, IA1). Yet new entrants typically possess state-of-the-art knowledge, as they often spin-off from universities or research institutes (NE1-3).

Knowledge diffusion

Although producers are developing knowledge on CCI, this knowledge is typically lacking on the demand side, which includes engineers, contracting companies and procurers (Vermeulen et al., 2007). Interviewees (NE3; EF4/6/8/12/13; IA4; P2–4) argued that this lack of knowledge inhibits CCI diffusion, as the demand side perceives it as too risky. Users also buy concrete in a routinized fashion as this has resulted in relatively cheap but high quality concrete, but as a consequence, concrete suppliers are involved in the procurement process too late to suggest CCI (NE3; EF1/6/8/12; IA4). This affects guidance of the search and market formation, as procurers, for example, rule out recycled concrete by always asking for the smoothest (CUR-100) concrete, even for fundaments that are not visible (EF12). Hence, more knowledge diffusion is needed, but interviewees (NE1/3; EF11-13; IA4; P2) indicated that learning by interacting and by using is limited due to the conservative nature of users. They argued that current training courses and educational programs focus too much on traditional materials. Only larger firms have the resources to provide additional training and information.

Guidance of the search

Historically, concrete innovations aim to incrementally enhance strength and durability, with emissions becoming increasingly important (Interviewees (Dewald and Achternbosch, 2015; EF2/5/8/11/13; IA3; P1). Consequently as Table 2 shows, various CCI are developing that affect different links in the supply chain and that may be complementary or mutually exclusive. For commercial success, these innovations need to comply with the norm and certification committees that are dominated by established firms. These committees are very conservative and risk-averse and pose formidable barriers to the commercialization of CCI (NE1/3; EF6/10; P2). Interviewees (NE1/3; EF4/9/10/13) for example indicated that a radically new alternative material had to comply with the norms for reinforced concrete, causing it to be 15 times stronger than demanded. These norms are created and maintained by established firms seated in the committees and who are the only ones that can change the norms for their own benefit. This institutional lock-in is further reinforced by prescriptive European standards that, as opposed to performance-based standards, inhibit CCI (Phair, 2006).

[10] Ranking respectively 195th and 212th in Europe in terms of R&D spending in 2013 (EU, 2014)

Other than through norm and certification committees, interviewees (NE1–3; EF1/2/9/13; IA2) indicated that established firms influence the guidance of the search in different ways, through influencing expectations, technology roadmaps and lobbying. In technology roadmaps, collectives of stakeholders assess the feasibility and emission reduction potential of innovations for the short, medium and long term. This process involves a form of selection through the consolidation and diffusion of expectations, as these documents are widely adopted by other stakeholders.

Expectations regarding CCI differ widely (Schneider et al., 2011; Scrivener, 2014). Firms attempt to influence expectations of these innovations by spreading information. Incumbents, positioning themselves as experts, have for example reported negatively on innovations by new entrants, affecting their sales (NE1/3; EF2/4/5/9/10; IA1).

Several interviewees indicated that their firm is in the Green Deal collective to represent their vested interests and influence the direction of innovation, for example through a roadmap study commissioned by the Dutch Ministry of Infrastructure and the Environment. In this study, the Green Deal members first identified 70 CCI and reduced them to the 16 depicted in Table 2 (van Lieshout, 2015). Interviewees (EF4/12/13; P4) indicated that innovations that were not of interest to the Green Deal members or for which quantitative data was missing were excluded. Similarly, the Dutch cement association drafted a roadmap that underlines the importance of safety, existing norms and proven technologies to the industry (Cement&BetonCentrum, 2012).

The global association WBCSD (2009; p.9) argues in their 2050 roadmap that because more radical CCI are initially limited to niche markets, it is "not known whether they can have an impact on the future cement industry. As a result they have not been included in the roadmap analysis". Omitting more radical clean innovations from 2050 roadmaps is highly problematic as academic literature indicates that without these innovations, 2050 emission reduction targets in energy-intensive processing industries like concrete cannot be met (Allwood et al., 2010; Dewald and Achternbosch, 2015; Hasanbeigi, 2013; Lechtenböhmer et al., 2015a;b; Wesseling et al., forthcoming).

Market formation

Industry has developed various solutions to making concrete more sustainable, but demand and policy support is typically lacking for these cleaner innovations (van Lieshout, 2014; NE2; EF2-13; IA4; P1-3]).

Through its dual role as policy maker and largest procurer of concrete, the public agencies are in the unique position to form markets for clean concrete. In their procurement policy, Dutch agencies give suppliers a fictitious reduction on the bidding price of their proposal, based on 1) an environmental life cycle assessment tool and/or 2) a carbon certification system that relies on emission reductions within the company and its supply chain. The "cleaner" the proposal, the higher the fictitious reduction. Although many interviewees (NE3; EF2-6/10/-13; IA4; P1-3) state that this is good policy in principle, at the same time they identified it as a systemic problem, because:

1) in practice it is the price that counts, not the carbon performance (EF2–7/10/12/13; IA4)
2) the policy is not enforced, resulting in suppliers promising emission reductions that they do not realized (EF4/12; P1/3)

3) all incumbents are already at the highest level of the carbon certification system; it therefore provides no impetus to sustainability (EF2/4/8/12/13; IA5; P4)
4) the life cycle assessment (LCA) tool is too rigid and excludes many innovations (EF8/13; IA2/5; P2)
5) procuring project managers are risk-averse and not rewarded for clean innovations (NE3; EF1/6/12; IA4; P2/3); this risk-aversion may result in a time to full market penetration of over 20 years (Dewald and Achternbosch, 2015)[11]

A successful case of public procurement of clean concrete (projectbureau Zeeweringen) indicates that the policy should be able to demand cleaner concrete over time and that, in line with the literature on public procurement for innovation (Edquist and Zabala, 2012; Wesseling and Edquist, 2016), procurement should be based more on function and not on product description.

Regulations on CCI are limited both at the national and European level. Firms follow minimum requirements, such as energy performance norms. Interviewees (EF5–8/11–13; IA2/3) indicated that their firms will become more sustainable when the policy support and regulations are there. One interviewee (EF7) indicated that volatile regulations have resulted in a short-term strategy. Regulations like the EU-emission trading scheme (EU ETS) help in providing a long-term vision, although its carbon price is too low to be of influence. Several interviewees (EF5/6/13) indicated however that they are preparing for higher carbon prices.

Resource mobilization

Like other energy-intensive processing industries, the concrete industry is characterized by high sunk costs, by high capital-intensity and by a low value-added commodity with low profit margins (Scrivener and Kirkpatrick, 2008; Wesseling et al., forthcoming). Hence, little capital is available, where much is needed. This inhibits innovation, particularly for smaller firms, entails a barrier to entry and has resulted in production dominated by a few global players (NE1; EF4/6/7/8/13; IA2/3; Dewald and Achternbosch, 2015).

Compliance with and influence of the conservative regulations, norms and certification processes require significant allocation of time, personnel and financial resources. Such resources are typically only available to the large incumbents (NE3; EF1/13). Established firms (EF3/4/6/8/11) indicate that the recent economic crisis, which led to a 30% decrease in concrete consumption and bankruptcies of several mortar companies (Cement&BetonCentrum, 2012), made it almost impossible to attract external capital. This is problematic since particularly commercial introduction and upscaling of clean innovations require significant capital (NE1/2). Interviewees (NE1/2/4; EFC8) indicated that the core of the financing problem lies in them having to advance the payment for natural resources, but that larger contractors only pay them after 60–120 days. Bridging this gap is problematic for starters that cannot attract external capital and have insufficient private equity.

Creation of legitimacy

Like other basic materials, end-users are far removed from concrete production and public pressure on clean concrete is therefore often limited (Wesseling et al., forthcoming), although there is more

[11] As in other energy-intensive processing industries, market-penetration times for specialized products (like prefab) are much shorter (Wesseling et al., forthcoming).

focus on eco-efficiency in the use phase (Dewald and Achternbosch, 2015). Clean concrete is simply not visible to the user; "it is still gray" (EF12). Nevertheless, larger companies (EF4/6/7) indicated that a "green image" does play a role in their decision-making.

The concrete industry is characterized by high levels of industry coordination, extending even to illegal cartels in the 1990s and early 2000s (Dumez and Jeunemaitre, 1999; Friederiszick and Roller, 2010). Dewald and Achternbosch (2015) argue that the strong shared interests underpinning this coordination results from the lack of product differentiation in the industry. Political coordination takes place in a network of industry associations[12] that represent established firms of different sizes at the national and European level. Other than the Dutch (VOBN) and European (ECP) concrete associations, there are also associations for more specific sectors, like cement (Cembureau), and for broader sectors (e.g. the Alliance of Energy Intensive Industries). The concrete industry associations tend to be defensive toward clean concrete regulations (EF7/9/10), which typically conflict with their mission of "promot[ing] the use of concrete in buildings and constructions" (VOBN-beton, 2016, p.1). Vermeulen et al. (2007) find that by spreading negative expectations to both concrete manufacturers and buyers, these associations pose a formidable barrier to market formation.

The established firms (EF1/2/4) indicated that when the pressure for clean innovation gets strong enough, they will use their power to steer the direction of clean innovation in ways that benefit their interests. They have already done so by the mechanisms indicated under system function guidance of the search.

Overall functioning of the innovation system

For each system function, Table 3 provides an overview of the systemic problems that hamper the development and diffusion of CCI in the Netherlands. The table shows that systemic problems occur in all structural components of the SSI, including actors, networks, institutions, technology, and infrastructure. Although all system functions are affected by the systemic problems, the most significant problems relate to the system functions necessary to launch CCI on the market, including market formation, entrepreneurial activities, knowledge diffusion, guidance of the search, and resources mobilization. Knowledge development is less of a bottleneck to system development.

Table 3, Overview of systemic problems that inhibit the development and diffusion of CCI.

System function	**Systemic problem**	**Structural component**
SF1: Entre-preneurial activities	Entry barriers formed by vertically integrated industry structure and concentrated market	*Actor/Network*
	Supply-chain specific (and general) vested interests: reduces tendency to commercialize CCI	*Actor*
SF2: Knowledge development	Long time horizon of concrete: hampers learning by experimentation in mainstream market segments (testing facilities are expensive)	*Technology*
SF3: Knowledge diffusion	Concrete producers involved too late in procurement process: no more room for knowledge diffusion	*Network*
	Demand side's lack of knowledge about CCI: too high risk perception	*Actor*
SF4: Guidance	Demand side's focus on safety and low expectations regarding CCI:	*Actor/Institution*

[12] Vermeulen et al. (2007) identified 72 associations that had an interest in the concrete industry.

of the search	guide the search away from CCI	
	Conservative demand side: inhibits knowledge diffusion	*Actor/Institution*
	Supply-chain specific (and general) vested interests: affects which CCI are selected in technology roadmaps and commissioned studies which provides solidification and diffusion of expectations	*Actor/Institution*
	Incumbents protect vested interests: by shaping expectations	Actor
	Collectives and associations dominated by established firms reinforce the influence of vested interests: guides the search toward CCI favorable to their vested interests	*Network*
SF5: Market formation	Procurers are not willing to pay price premium for CCI: no market or policy support	*Actor/Institution*
	Risk-aversion among procurers: no demand for CCI	Actor
	Rigid LCA tools: excludes many CCI - no market incentive	*Formal institution*
	Carbon certification system not challenging enough: no impetus for firms to do CCI	*Formal institution*
	CCI support policy not enforced: market policy not taken seriously	*Formal institution*
	Regulations on CCI are lacking and provide no long-term view (EU ETS too weak): no drive for CCI	*Formal institution*
SF6: Resource mobilization	High cost of innovation and low profit margins: reduces availability of sufficient resources to engage in entrepreneurial activities and knowledge development, particularly within smaller firms	*Technology*
	Capital intensity: creates barriers to entry	*Infrastructure*
	Regulations, norms and certificates: require time, capital and influence to comply with/change	*Institution*
	Very hard to attract external capital: hampers entrepreneurial activities.	*Network*
SF7: Creation of legitimacy	Concrete is far removed from the public: little pressure for CCI	*Actor*
	Strong shared interests: easy to organize collective lobbying and strong self-governance culture	*Network*

4.3 Interdependence of systemic problems

Based on the previously discussed coupled structural-functional analysis, Figure 3 provides an overview of the systemic problems (rectangles), the effects they have on system function performance (ovals) and how this translates into interdependence (represented by arrows). For sake of clarity, the demand and regulative side of the innovation system are in green and the industry side in blue.

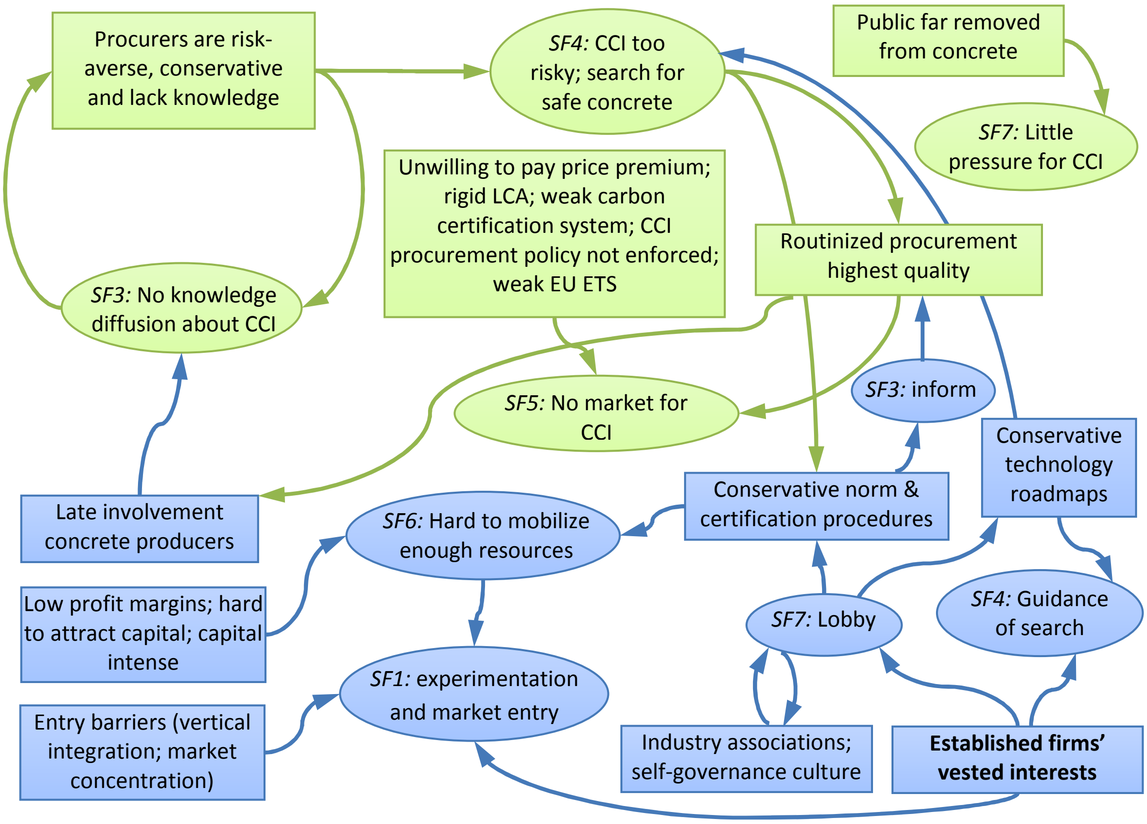

Figure 3, Interdependencies between systemic problems (rectangles) and their effects on system functions (ovals); distinguishing the public, demand, and regulative sides of the innovation system (green) and the industry side (blue).

The demand side's (particularly the procurers') conservative attitude inhibits knowledge diffusion, particularly since concrete producers get involved in the routinized procurement process too late. This results in a lack of knowledge diffusion to procurers of concrete, whom consequently develop a preference for safe concrete and a perception of CCI as being "too risky". This behavior has become institutionalized in routinized procurement for high-quality, certified concrete that complies with conservative norms. Because this routinized behavior preempts CCI, there is no market for such innovations.

This lack of a market is reinforced by systemic problems like the unwillingness to pay a price premium, the rigid LCA tools that do not include all CCI, the weak carbon certification system, and the fact that CCI procurement policies are not enforced. At the European level, the EU–ETS is too weak to trigger industry to sell CCI. Finally, there is little public pressure to buy and produce CCI, as the public is far removed from concrete.

On the industry side we find that because of vested interests, established firms do little commercial experimentation with CCI and even strategically create and sustain systemic problems to CCI development and diffusion. These vested interests are to a large extent specific to the firm's activities in the supply chain, which affects how the firm and sector-specific associations influence systemic problems. Established firms have for example reported negatively on the CCI of new entrants. Reinforced by well-organized industry associations and enabled by the industry's self-governance culture, established firms are influential in shaping technology roadmaps and norm and certification procedures. They influence roadmaps to solidify and spread expectations regarding the direction of CCI. This affects the industry side and reinforces the idea among procurers that the CCI, seemingly assessed as unfeasible by the industry at large, are too risky to procure, which translates into a barrier to market formation. These roadmaps conflict fundamentally with the academic discourse on what CCI is feasible and necessary.

The conservative norm and certification procedures are often not flexible enough to include CCI. Since the routinized procurement only includes certified concrete that complies with the norms, market formation is indirectly affected. Norm and certificate compliance is very time and capital consuming, which creates a barrier to entry and inhibits experimentation, particularly since low profit margins and the inability to attract external capital strain resources. Moreover, only established firms have the influence to change these procedures to facilitate CCI. Barriers to entry are further increased by vertical integration and the capital intensive infrastructure.

To recap, the systemic problems on the demand and regulatory side are different from and interdependent with those on the industry side; vested interests are shown to induce and sustain several of these systemic problems.

5. Conclusion and policy recommendations

This study explains, through identifying a set of interdependent systemic problems, why so few clean innovations are diffusing in the Dutch concrete industry. These systemic problems cover the regulatory and demand side, e.g. ineffective public policy and conservative (mostly public) procurers that lack knowledge and procure routinely, as well as the industry side. Vested interests play an important role, as various established firms, particularly powerful incumbents, are found to individually and/or collectively act strategically to induce or sustain these systemic problems to protect their business cases. The system functions affected by these strategically induced systemic problems include guidance of the search, entrepreneurial activities, market formation, and resources mobilization. To support the diffusion of CCI, these systemic problems and the underlying methods of strategic influence need to be mitigated.

In the light of this special volume, our paper highlights that the business cases and vested interests of established firms differ along the supply chain. Often, established firms find CCI less profitable than their existing business case. Instead, their vested interests incentivize them to engage in strategic influence and induce or sustain systemic problems that inhibit the development and diffusion of these CCI. These private vested interests conflict with the public interests in a cleaner concrete industry. Policy interventions to mitigate the inhibiting power of these vested interests may therefore be warranted.

This case study focused on the Netherlands, but the findings on the prominence of vested interests and systemic lock-in are expected to be generalizable to the European concrete industry. First, due to high transportation cost of a relatively cheap product, this industry is relatively similar across Europe, i.e. concentrated ownership, with local concrete production with more centralized mining and cement production. Second, since the Netherlands imports most of its cement, the cement lobby should be less influential compared to other EU countries, in inhibiting CCI to protect their vested interests. Third, Dutch concrete production and consumption is relatively clean, implying that

CCI are diffusing better than in other European countries. The latter two factors suggest that vested interests and systemic lock-in may be even more prominent in other European countries.

Applying the structural-functional approach to mature, sectorally-delineated innovation systems instead of to emerging TIS (as is conventionally done) provided several benefits. First, it enabled the analysis of a transforming established socio-technical system, the Dutch concrete industry, toward sustainability at a certain point in time. Second, this enables the identification of systemic problems that are not only related to inhibiting system growth, but also to inhibiting system transformation (Weber and Rohracher, 2012). Third, since established systems are characterized by stronger interdependencies, it facilitated the study of interdependent systemic problems. Fourth, it enabled the study of the role of established firms' vested interests when confronted with such transformation and how they may strategically induce or sustain systemic problems. Hence, applying the system functions approach to a transforming sector or industry instead of to an emerging technology or product, has proved a fruitful venue for further research.

5.1 Policy recommendations

Facilitating systemic transformation to sustainable production requires a comprehensive mix of policy instruments that both supports radical innovation and puts pressure on the established regime (Kivimaa and Kern, 2015). The numerous interdependent systemic problems we identified require specific instruments; here we focus on those mitigating vested interests, which underlies many systemic problems, and on those directly driving the diffusion of CCI.

Reducing the power behind these vested interests, such as the industry's high level of self-governance, requires significant changes in regime rules. First, policy makers should realize that it is often unfruitful to discuss innovation policy with collectives like industry associations that are dominated by vested interests. These collectives typically take the position of their most defensive member because there is no collective benefit in adopting clean innovations that result in a less profitable status quo. Second, policy makers should minimize the chance that commissioned studies to explore CCI are captured by vested interests, for example by approaching more neutral actors like knowledge institutes and by requiring more objective data. Third, a similar approach should be taken for technology roadmaps. Policy makers have used such tools increasingly to build collective future visions and overcome the directionality failure of system transformation (Weber and Rohracher, 2012), but as we show in this paper, it is should be recognized that they can also be used as political instruments for vested interests. Fourth, norm and certification committees dominated by vested interests are a common bottleneck to innovation (Smink et al., 2015) and should instead be comprised of more neutral experts that ensure that the procedures become more open to radically new CCI. Fifth, building on the idea that policy makers need to develop objective consultation, they also need to develop, preferably in-house, the expertise to critically assess the potentially biased external information and to perform well-informed procurement.

The added-value of understanding interdependency of systemic problems lies in going beyond policy recommendations like stimulating knowledge diffusion to overcome the problem of procurers lacking knowledge. Instead we can recommend how to enhance the quality of the knowledge diffused.

Finally, control policies to stimulate CCI uptake are particularly effective because public agencies are the largest procurers of concrete. These policy makers should engage in functional procurement based on the functions that need to be fulfilled (including emission reductions) instead of on the way the product is made. This constitutes a technology-neutral control policy that excludes carbon-intensive solutions, as companies can decide for themselves whether to cut emissions by using less concrete, by replacing polluting resources and/or by recycling materials. These functional requirements should demand more sustainability over time and include tools flexible enough to properly assess more radical CCI. These policies should also be better enforced than is currently done, and suppliers' inability to deliver should be penalized. This control policy requires however that public agencies pay a risk and price premium for CCI because it is less proven and sometimes more expensive than conventional concrete. Finally, the CO_2 prices are too low under the current EU ETS to stimulate CCI; for this purpose interviewees indicate that a price of at least 30 euro per ton is necessary. Such financial incentives are particularly effective to stimulate CCI, due to the industry's decentralized production and strong price competition.

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References

Åhman, M., Nikoleris, A., Nilsson, L.J., 2012. Decarbonising industry in Sweden - an assessment of possibilities and policy needs. Lund University.

Aitcin, P., 2000. Cements of yesterday and today Concrete of tomorrow. Cement Concrete Res. 30, 1349–1359.

Allwood, J.M., Cullen, J.M., Milford, R.L., 2010. Options for achieving a 50% cut in industrial carbon emissions by 2050. Environ. Sci. Technol. 44, 1888–1894. doi:10.1021/es902909k

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., Truffer, B., 2015. Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. Environ. Innov. Soc. Transitions. doi:10.1016/j.eist.2015.07.003

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., Truffer, B., 2015. Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. Environ. Innov. Soc. Transit. 16, 51–64. doi:10.1016/j.eist.2015.07.003

Bijleveld, M.M., Bergsm, G.C., van Lieshout, M., 2013. Milieu-impact van betongebruik in de Nederlandse bouw, Status quo en toetsing van verbeteropties. CE Delft, Delft.

Carlsson, B., Stankiewicz, R., 1991. On the nature, function and composition of technological systems. J. Evol. Econ. 93–118.

Cement&BetonCentrum, 2012. Roadmap duurzaam cement. http://www.cementenbeton.nl/duurzaam-bouwen/cement-en-co2 (accessed 29.01.16)

CementenBeton, 2016. Betonmarkt. http://www.cementenbeton.nl/marktinformatie/betonmarkt (accessed 29.01.16)

Chaminade, C., Edquist, C., 2010. Rationales for public policy intervention in the innovation process: A systems of innovation approach, in: Smits, R., Kuhlman, S., Shapira, P. (Eds.), The Theory and Practice of Innovation Policy. An International Research Handbook. Edward Elgar, Cheltenham, pp. 95–114.

Coenen, L., Díaz López, F.J., 2010. Comparing systems approaches to innovation and technological change for sustainable and competitive economies: An explorative study into conceptual commonalities, differences and complementarities. J. Clean. Prod. 18, 1149–1160. doi:10.1016/j.jclepro.2010.04.003

Dewald, U., Achternbosch, M., 2015. Why did more sustainable cements failed so far? Disruptive innovations and their barriers in a basic industry. Environ. Innov. Soc. Transitions 1–16. doi:10.1016/j.eist.2015.10.001

Dumez, H., Jeunemaitre, A., 1999. Understanding and regulating the market at a time of globalization. The case of the cement industry. Macmillan Press, London.

Edquist, C., Zabala-Iturriagagoitia, J.M., 2012. Public Procurement for Innovation as mission-oriented innovation policy. Res. Policy 41, 1757–1769. doi:10.1016/j.respol.2012.04.022

EU, 2014. The 2014 EU Industrial R&D Investment Scoreboard. http://iri.jrc.ec.europa.eu/scoreboard14.html (accessed 29.01.16)

Faber, A., Hoppe, T., 2013. Co-constructing a sustainable built environment in the Netherlands-Dynamics and opportunities in an environmental sectoral innovation system. Energ. Policy 52, 628–638. doi:10.1016/j.enpol.2012.10.022

Friederiszick, H.W., Roller, L.-H., 2010. Quantification of harm in damages actions for antitrust infringements: Insights from German cartel cases. J. Compet. Law Econ. 6, 595–618. doi:10.1093/joclec/nhq008

Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. Res. Policy 33, 897–920. doi:10.1016/j.respol.2004.01.015

Galli, R., and Teubal, M. (1997). Paradigmatic shifts in national innovation systems. In C. Edquist (Ed.), Systems of innovation: Technologies, institutions and organizations (pp. 342-370). London: Pinter.

Hansen, T., Coenen, L., 2015. The geography of sustainability transitions: Review, synthesis and reflections on an emergent research field. Environ. Innov. Soc. Transit. 17, 92–109. doi:10.1016/j.eist.2014.11.001

Hasanbeigi, A., 2013. Emerging Energy-efficiency and CO2 Emission-reduction Technologies for Cement and Concrete Production.

Hekkert, M.P., Hendriks, F.H.J.F., Faaij, a. P.C., Neelis, M.L., 2005. Natural gas as an alternative to crude oil in automotive fuel chains well-to-wheel analysis and transition strategy development. Energy Policy 33, 579–594. doi:10.1016/j.enpol.2003.08.018

Hekkert, M.P., Negro, S.O., 2009. Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims. Technol. Forecast. Soc. Change 76, 584–594. doi:10.1016/j.techfore.2008.04.013

Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., 2007. Functions of innovation systems: A new approach for analysing technological change. Technol. Forecast. Soc. Change 74, 413–432. doi:10.1016/j.techfore.2006.03.002

Jacobsson, S., Bergek, A., 2011. Innovation system analyses and sustainability transitions: Contributions and suggestions for research. Environ. Innov. Soc. Transit. 1, 41–57. doi:10.1016/j.eist.2011.04.006

Kieft, A., Harmsen, R., Hekkert, M., 2016. Interactions between systemic problems in innovation systems: The case of energy-efficient houses in the Netherlands. Innov. Stud. Utr.

Kivimaa, P., Kern, F., 2015. Creative Destruction or Mere Niche Creation? Innovation Policy Mixes for Sustainability Transitions. Res. Policy 02, 29. doi:10.1016/j.respol.2015.09.008

Klein-Woolthuis, R., Lankhuizen, M., Gilsing, V., 2005. A system failure framework for innovation policy design. Technovation 25, 609–619. doi:10.1016/j.technovation.2003.11.002

Lamprinopoulou, C., Renwick, A., Klerkx, L., Hermans, F., Roep, D., 2014. Application of an integrated systemic framework for analysing agricultural innovation systems and informing innovation policies: Comparing the Dutch and Scottish agrifood sectors. Agric. Syst. 129, 40–54. doi:10.1016/j.agsy.2014.05.001

Lechtenböhmer, S., Nilsson, L., Åhman, M., Schneider, C., 2015. Decarbonising the energy intensive basic materials industry through electrification Paper submitted to SDEWES 2016. Lund Univ. Publ.

Lechtenböhmer, S., Schneider, C., Roche, M., Höller, S., 2015. Re-industrialisation and low-carbon economy—Can they go together? Results from stakeholder-based scenarios for energy-intensive industries in the German state of North Rhine Westphalia. Energies 8, 11404–11429. doi:10.3390/en81011404

Malerba, F., 2002. Sectoral systems of innovation and production. Res. Policy 31, 247–264. doi:10.1016/S0048-7333(01)00139-1

Malerba, F., 2004. Sectoral systems of innovation: concepts, issues and analyses of six major sectors in Europe. Cambridge University Press.

Markard, J., Hekkert, M., Jacobsson, S., 2015. The technological innovation systems framework: Response to six criticisms. Environ. Innov. Soc. Transit. 16, 76–86. doi:10.1016/j.eist.2015.07.006

Markard, J., Truffer, B., 2006. Innovation processes in large technical systems: Market liberalization as a driver for radical change? Res. Policy 35, 609–625. doi:10.1016/j.respol.2006.02.008

Markard, J., Truffer, B., 2008. Actor-oriented analysis of innovation systems: exploring micro–meso level linkages in the case of stationary fuel cells. Technol. Anal. Strateg. Manag. 20, 443–464. doi:10.1080/09537320802141429

Negro, S.O., Alkemade, F., Hekkert, M.P., 2012. Why does renewable energy diffuse so slowly? A review of innovation system problems. Renew. Sust. Energ. Rev. 16, 3836–3846. doi:10.1016/j.rser.2012.03.043

Negro, S.O., Hekkert, M.P., Smits, R.E., 2007. Explaining the failure of the Dutch innovation system for biomass digestion - A functional analysis. Energ. Policy 35, 925–938. doi:10.1016/j.enpol.2006.01.027

Patana, A.S., Pihlajamaa, M., Polvinen, K., Carleton, T., Kanto, L., 2013. Inducement and blocking mechanisms in the Finnish life sciences innovation system. Foresight 15, 428–445. doi:10.1108/FS-10-2012-0081

Penna, C.C.R., Geels, F.W., 2015. Climate change and the slow reorientation of the American car industry (1979-2012): An application and extension of the Dialectic Issue LifeCycle (DILC) model. Res. Policy 44, 1029–1048. doi:10.1016/j.respol.2014.11.010

Phair, J.W., 2006. Green chemistry for sustainable cement production and use. Green Chem. 8, 763. doi:10.1039/b603997a

Raven, R., Kern, F., Smith, A., Jacobsson, S., Verhees, B., 2016. The politics of innovation spaces for low-carbon energy: Introduction to the special issue. Environ. Innov. Soc. Transit. 18, 101–110. doi:10.1016/j.eist.2015.06.008

Schneider, M., Romer, M., Tschudin, M., Bolio, H., 2011. Sustainable cement production-present and future. Cem. Concr. Res. 41, 642–650. doi:10.1016/j.cemconres.2011.03.019

Scrivener, K.L., Kirkpatrick, R.J., 2008. Innovation in use and research on cementitious material. Cem. Concr. Res. 38, 128–136. doi:10.1016/j.cemconres.2007.09.025

Scrivener, K.L., 2014. Options for the future of cement. Indian Concr. J. 11–21.

Smink, M.M., Hekkert, M.P., Negro, S.O., 2015. Keeping sustainable innovation on a leash? Exploring incumbents' institutional strategies. Bus. Strateg. Environ. 24, 86–101. doi:10.1002/bse.1808

Suurs, R., Hekkert, M.P., 2009. Cumulative causation in the formation of a technological innovation system: The case of biofuels in the Netherlands. Technol. Forecast. Soc. Change 76, 1003–1020. doi:10.1016/j.techfore.2009.03.002

Teece, D.J., Pisano, G., Shuen, A., 1997. Dynamic Capabilities and Strategic Management Cap. 6, 77–115. doi:10.1002/(SICI)1097-0266(199708)18:7<509::AID-SMJ882>3.0.CO;2-Z

Turner, J.A., Klerkx, L., Rijswijk, K., Williams, T., Barnard, T., 2016. Systemic problems affecting co-innovation in the New Zealand Agricultural Innovation System: Identification of blocking mechanisms and underlying institutional logics. NJAS - Wageningen J. Life Sci. 76, 99–112. doi:10.1016/j.njas.2015.12.001

Utterback, J.M., Suarez, F.F., 1993. Structure, Competition, and Industry. Res. Policy 22, 1–21.

Van der Vooren, A. Reudink, M. and Hanemaaijer, A., 2015. Eco-innovatie in gevestigde productieketens, Een analyse van de beton- en de glastuinbouwketen. PBL. Den Haag.

Van Lieshout, M., 2015. Update Prioritering handelings- perspectieven verduurzaming quickscan van 16 door het MVO Netwerk Colofon. CE Delft. Delft.

Van Lieshout, M., 2014. Voorbereiding convenant Concreet 2.0 binnen de Green Deal Beton. CE Delft. Delft.

Van Mierlo, B., Leeuwis, C., Smits, R., Woolthuis, R.K., 2010. Learning towards system innovation: Evaluating a systemic instrument. Technol. Forecast. Soc. Change 77, 318–334. doi:10.1016/j.techfore.2009.08.004

Van Oss, H.G., Padovani, A.C., 2003. Cement manufacture and the environment- Part II: Environmental challenges and opportunities. J. Ind. Ecol. 7, 93–126. doi:10.1162/108819802320971650

Vermeulen, P., Buch, R., Greenwood, R., Vermeulen, P., Buch, R., Greenwood, R., 2007. The Impact of Governmental Policies in Institutional Fields: The Case of Innovation in the Dutch Concrete Industry. Organ. Stud. 28, 515–540. doi:10.1177/0170840606067927

VOBN-beton, 2016. Vereniging betonmortelfabrikanten. http://www.vobn-beton.nl/vereniging-vobn/vereniging-betonmortelfabrikanten (accessed 29.01.16)

WBCSD. 2009. Cement Technology Roadmap 2009 Carbon emissions reductions up to 2050" World Business Council for Sustainable Development.

Weber, K.M., Rohracher, H., 2012. Legitimizing research, technology and innovation policies for transformative change: Combining insights from innovation systems and multi-level perspective in a comprehensive "failures" framework. Res. Policy 41, 1037–1047. doi:10.1016/j.respol.2011.10.015

Wesseling, J., Åhman, M., Coenen, L., Lechtenböhmer, S., Nilsson, L., Vallentin, D., Worrell, E., forthcoming. Decarbonizing energy-intensive processing industries: stylized facts and research agenda. Pap. Innov. Stud.

Wesseling J.H., Edquist C. 2016. Public procurement for innovation: lessons from the procurement of a navigable storm surge barrier. Pap. in Innov. Stud.

Wesseling, J.H., Farla, J.C.M., Hekkert, M.P., 2015. Exploring car manufacturers' responses to technology-forcing regulation: The case of California's ZEV mandate. Environ. Innov. Soc. Transit. 1–19. doi:10.1016/j.eist.2015.03.001

Wieczorek, A.J., Hekkert, M.P., 2012. Systemic instruments for systemic innovation problems: A framework for policy makers and innovation scholars. Sci. Public Policy 39, 74–87. doi:10.1093/scipol/scr008

Worrell, E., Berkel, R. Van, Fengqi, Z., Menke, C., Schae, R., Williams, R.O., 2001. Technology transfer of energy efficient technologies in industry : a review of trends and policy issues. Energy Policy 29, 29–43. doi:10.1016/S0301-4215(00)00097-5