



# Lock-in of mature innovation systems: the transformation toward clean concrete in the Netherlands



Joeri Hendrik Wesseling<sup>a, b, \*</sup>, Alexander Van der Vooren<sup>c</sup>

<sup>a</sup> Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CS, Utrecht, The Netherlands

<sup>b</sup> CIRCLE, Lund University, Sölvegatan 16, SE-221 00, Lund, Sweden

<sup>c</sup> PBL Netherlands Environmental Assessment Agency, Sustainable Development Department, PO Box 303, 3720AH, Bilthoven, The Netherlands

## ARTICLE INFO

### Article history:

Received 31 January 2016

Received in revised form

22 July 2016

Accepted 23 August 2016

Available online 24 August 2016

## ABSTRACT

Energy-intensive processing industries like the concrete industry form the base of the economy and account for a large part of global greenhouse gas emissions. Sectoral transformation to cleaner basic materials is therefore crucial, and institutional pressure to do so is increasing. However, socio-technical studies have not sufficiently addressed these sectors. 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 and diffusion of clean concrete innovations, for the case of the Netherlands. A 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 closed cycles of interdependent systemic problems and vested interests that characterize mature innovation systems and that hamper system transformation. 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 sustained through systemic lock-in, i.e. closed cycles of interdependent systemic problems. Through strategic, often collective action, established firms with vested interests were able to reinforce these interdependent 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. Overcoming systemic lock-in requires a series of well coordinated policy measures that should be implemented in a specific order, to prevent reverting back to the lock-in around the original system configuration.

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## 1. Introduction

The 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. Because energy-intensive processing industries have received little attention in this literature and are characterized by distinctive innovation system characteristics and sustainability transition dynamics, there is little understanding of why clean innovations do not diffuse within these industries (Åhman et al., 2012; Wesseling et al., forthcoming). Energy-intensive industries form the base of the economy by providing the materials on which our society relies and are responsible for a large share of GHG emissions (Fischedick et al., 2014). The concrete industry, ranging from the mining and processing of resources to

\* Corresponding author. Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CS, Utrecht, The Netherlands.

E-mail address: [j.h.wesseling@uu.nl](mailto:j.h.wesseling@uu.nl) (J.H. Wesseling).

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 approximately 5% of global CO<sub>2</sub> emissions (Huntzinger and Eatmon, 2009). 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 et al., 2012; Van Lieshout, 2015). This paper analyzes why these CCI are not diffusing.

The structural-functional approach is useful for this purpose, as it enables the identification of systemic problems that inhibit the functioning of innovation systems (Negro et al., 2012). The function of an innovation system is to develop, diffuse and utilize innovation so that user needs can be met under changing conditions (Malerba, 2004; Hekkert et al., 2007). 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). This paper however argues that it is also applicable to study the transformation of mature sectoral systems of innovation and production (SSI) like that of the concrete industry. Over the past century and more, this sector has settled around mature technologies,<sup>1</sup> 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 and diffusion 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 may lead to interdependent systemic problems (Carlsson and Jacobsson, 1997; Kieft et al., 2016; Negro et al., 2012). These interactions may even lead to systemic lock-in which, this paper argues, takes place when interdependent systemic problems sustain each other through one or more closed feedback cycles. Third, vested interests are found to inhibit the transformation of mature industries to clean innovation (Smink et al., 2015; Wesseling et al., 2015) and are expected to affect the concrete industry as well (Dewald and Achternbosch, 2015). The current study complements the structural-functional approach with a critical analysis of these, so far, overlooked characteristics (Kieft et al., 2016; Negro et al., 2012) to enable the analysis of transforming mature SSI.

The main contribution of the paper thus lies in developing the structural-functional approach to 1) enable the analysis of mature innovation systems, such as those of energy-intensive processing industries; 2) analyze the concept of systemic lock-in, which may help to explain the slow transformation of these mature innovation systems; 3) identify the role of vested interests in supporting systemic problems and lock-in. The insights from this study provide recommendations for a set of coordinated policy measures to overcome systemic lock-in and support CCI.

Like most structural-functional analyses (Coenen et al., 2012), the focal innovation system of this case study is nationally-delineated to enable in-depth analysis of the system. This case

study focuses on the Dutch concrete industry, but its findings are expected to be generalizable to other European countries as well, because the industry is relatively similar across Europe, i.e. concentrated ownership, with local concrete production and more centralized mining and cement production.

The subsequent Theory Section discusses innovation system delineation, transformation, lock-in and finally the use of the structural-functional approach to study the transformation of SSI instead of 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 how the interdependencies of the systemic problems lead to systemic lock-in. Conclusions and policy recommendations are provided in Section 5.

## 2. Theory

### 2.1. Innovation system delineation

Innovation systems are defined by their structural components, i.e. the actors,<sup>2</sup> networks, institutions and technology<sup>3</sup> that contribute to the development and diffusion 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 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 typically embedded in broader contexts at the sectoral level, such as construction, and the subsectoral or industrial level, like the concrete or steel industry. SSI are 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) and can be delineated at any of these sectoral levels. Within these sectoral levels, different TIS may be identified at the product level (e.g. concrete), the component level (e.g. geopolymers) or the knowledge field (e.g. alternative binding materials) (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). Both TIS and SSI may furthermore span the national boundaries of innovation systems (NIS), see Fig. 1. In this figure the focus of this paper is represented by the striped area (comprising a nationally-delineated SSI that captures multiple TIS). When a TIS dominates an SSI, their boundaries may coincide.

### 2.2. Innovation system transformation

Since the 2000s, TIS studies have typically focused on emerging innovation systems in the formative phase and neglected mature systems (Hansen and Coenen, 2015) or relegated 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

<sup>1</sup> 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).

<sup>2</sup> Including for example firms, users, policy makers, research institutes and intermediary organizations.

<sup>3</sup> Sometimes referred to as materiality.

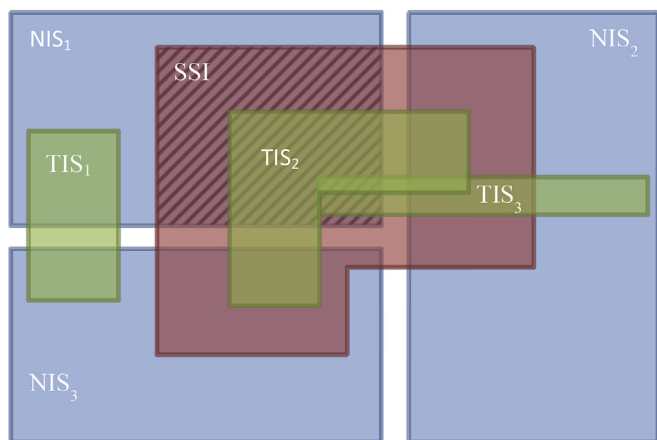


Fig. 1. Relations between innovation system boundaries and focus of the paper, adapted from Hekkert et al., 2007.

(Fig. 1, TIS<sub>2</sub>) and emerging TIS that are less aligned with the SSI (Fig. 1, TIS<sub>3</sub>). While the proper functioning of emerging TIS typically requires system growth (Hekkert et al., 2007), the long-term functioning of mature SSI under external pressure (such as climate change) revolves more around directional system transformation.<sup>4</sup> Both system growth and transformation involve changes in the structural components of the system. These components constitute systemic problems<sup>5</sup> when they inhibit system functioning. The innovation system literature is abundant with classifications of systemic problems.<sup>6</sup> Recognizing this diversity and complexity, this paper adheres to Wieczorek and Hekkert (2012) classification of systemic problems along the structural components of an innovation system.

In the context of system transformation, SSI transformation involves the development and diffusion 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. The replacement of cement with geopolymers for example affects a larger part of the supply chain than partially replacing clinker with blast furnace slag.

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 and diffusion 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). This results 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 structural components is expected to lead to interdependent systemic problems (Kieft et al., 2016; Negro et al., 2012).

Systemic problems are interdependent when one systemic problem leads to or reinforces another systemic problem. Turner et al. (2016) find such interdependencies in the agricultural sector, while Negro et al. (2012) provide the example of policy that inhibits innovation (problem 1), but where the policy cannot be improved due to misinformed policy makers (problem 2) and the inability of entrepreneurs to inform them (problem 3). 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. When interdependent systemic problems form closed feedback cycles, systemic lock-in may arise.

On this basis, this paper redefines the concept of systemic lock-in (Carlsson and Jacobsson, 1997; Narula, 2002), as a set of systemic problems that sustain or reinforce each other in one or more closed feedback cycles of interdependent systemic problems.<sup>7</sup> Understanding and overcoming the inability of an SSI to transform requires the untangling and coherent solving of the interdependent systemic problems that comprise systemic lock-in. This may not only result in a specific set of policy measures, but also in a specific order of implementation, as some systemic problems may need to be overcome before the problems they sustain or reinforce are targeted by subsequent and different policy measures.

Mature SSI are typically dominated by established firms that have vested interests in maintaining the status quo. To protect their profitable position, which is often technology-specific (Teece et al., 1997), and to deter new entrants, these 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), specifically by creating, sustaining or reinforcing systemic problems. 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., 2016).

### 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

<sup>4</sup> Analyzing sectoral transformation therefore enables the identification of both, what Weber and Rohrer (2012) label, structural and transformational system failures.

<sup>5</sup> 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).

<sup>6</sup> See for example Klein-Woolthuis et al. (2005); Negro et al. (2012); Weber and Rohrer (2012); Wieczorek and Hekkert (2012).

<sup>7</sup> This notion is different from cycles of negative causation (Suurs, 2009) that do not lead to stability of the system, but to its degeneration.

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 structural-functional approach has been developed (Bergek et al., 2008; Hekkert et al., 2007). Table 1 provides an overview and description of the system functions used in this paper. These 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).

System functions thus represent the effect of a systemic problem on system performance. Such effects may on themselves trigger new problems. System functions are therefore central to understanding the interdependence between problems. To illustrate with the previous example of interdependent problems: the inability of entrepreneurs (problem) results in a lack of knowledge diffusion (system function) towards policy makers, which impairs them from improving their innovation policy (problem). To support underdeveloped system functions, policy measures should address the systemic problems that affect them (Jacobsson and Bergek, 2011; Wieczorek and Hekkert, 2012).

Although the structural-functional approach has been applied predominantly to emerging TIS to assess system growth, it can be applied more broadly (Bergek et al., 2008; Coenen and López, 2010). System functions studies have extensively analyzed the agriculture sector (Kebebe et al., 2015; Lamprinou 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 structural-functional 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, a structural-functional approach was adopted that is characterized by several analytical steps (Bergek et al., 2008; Wieczorek and Hekkert, 2012). In addition to these steps, a fourth step was added to identify interdependencies between systemic problems as suggested by Kieft et al. (2016), enabling the study of more deeply embedded problems and of the role of established firms' vested interests. A fifth step is added to identify systemic lock-in. The analytical steps taken in this paper include:

1. Preliminary mapping out the SSI' 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. Identification of potential systemic lock-in, i.e. one or more closed cycles of interdependent systemic problems
6. Formulation of policy measures to alleviate potentially interdependent systemic problems

The performance of the system functions depicted in Table 1 is assessed using the widely employed operationalization scheme

(e.g. by Hekkert and Negro, 2009; Negro et al., 2007; Suurs, 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<sup>8</sup> included each type of firm along the supply chain of concrete, encompassing small and large established firms (15), many of 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. Following the functional analysis, systemic problems were identified that inhibited functional performance. After describing these problematic components, the interdependencies between them were identified. Seventeen stakeholders<sup>9</sup> 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

First, this section maps out the supply chain of concrete and its various clean innovations. It subsequently discusses the 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. The Netherlands produces 14–15 million cubic meters of concrete per year (CementenBeton, 2016), which accounts for 1.8% of national CO<sub>2</sub> 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); the only cement producer in the Netherlands (ENCI B.V.) is owned by multinational HeidelbergCement and will close in 2018. Dutch concrete is clean due to utilization of secondary fuels and partial replacement of cement with locally available alternative binders such as blast furnace slag and coal fly ash.

The supply chain of concrete is depicted in Fig. 2. Companies

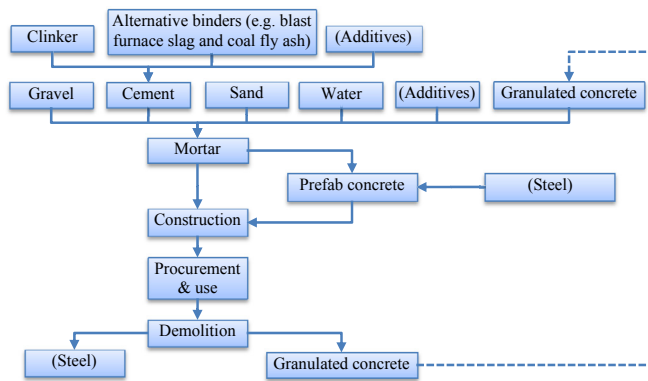
<sup>8</sup> Universities and research institutes were not interviewed because they focus on knowledge development (which functioned properly in this case) and not on the diffusion of innovations, which is where the system problems occur. Their spin-offs were included.

<sup>9</sup> Five out of seventeen are from the list of interviewees.



**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 SSI) 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  |



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

concrete SSI is characterized by product and process innovations aimed at incremental cost reduction through resource and energy efficiency.

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. The following analysis will identify systemic problems related to the development and diffusion of these and other CCI and will subsequently study the interdependence of these problems.

**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).

| Category                        | Specific CCI  |
|---------------------------------|---|
| Changes in concrete composition | Optimize grain distribution<br>Expand the resources allowed for making cement (CEM X)<br>Use calcium sulfoaluminate cements (CSA)<br>Use super sulphated cements<br>Use alternative CSH cement<br>Use geopolymers as cement |
| Reuse/recycling                 | Build with demountable standard units<br>Cement recycling via smart demolition and/or ADR (mechanical)<br>Thermal cement recycling<br>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<br>Reduce oversizing in design phase  |
| Increase lifetime               | Longer lifetime through flexible design<br>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  |

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

#### 4.2. Identification of systemic problems

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

**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         |
| SF2: Knowledge development       | Supply-chain specific (and general) vested interests: reduces tendency to commercialize CCI   | Actor                 |
| SF3: Knowledge diffusion         | Long time horizon of concrete: hampers learning by experimentation in mainstream market segments (testing facilities are expensive)   | Technology            |
| SF4: Guidance of the search      | 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                 |
|                                  | Demand side's focus on safety and low expectations regarding CCI: guide the search away from CCI  | Actor/<br>Institution |
|                                  | Conservative demand side: inhibits knowledge diffusion  | Actor/<br>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/<br>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/<br>Institution |
|                                  | Risk-aversion among procurers: no demand for CCI  | Actor                 |
|                                  | Rigid LCA tools: excludes many CCI - no market incentive  | Formal<br>institution |
|                                  | Carbon certification system not challenging enough: no impetus for firms to do CCI  | Formal<br>institution |
|                                  | CCI support policy not enforced: market policy not taken seriously  | Formal<br>institution |
|                                  | Regulations on CCI are lacking and provide no long-term view (EU ETS too weak): no drive for CCI  | Formal<br>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               |

#### 4.2.1. Entrepreneurial activities

As Table 2 indicates, the Dutch concrete industry is experimenting with different CCI. Established firms dominate this industry. Fifteen interviewees<sup>10</sup> 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 prefabricated 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 fundamentals 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 prefabricated 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 prefabricated market segments because they are more open to entrepreneurial experimentation as they are less regulated, less certificate-intensive and enable modular construction<sup>11</sup> (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.

#### 4.2.2. 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 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<sup>12</sup>, but the share of R&D for CCI is unknown. Although established firms may explore CCI through R&D, some of

<sup>11</sup> Poured concrete that forms the basis of a structure cannot be taken out, whereas prefabricated products are modular and can be replaced more easily.

<sup>12</sup> Ranking respectively 195th and 212th in Europe in terms of R&D spending in 2013 (EU, 2014).

<sup>10</sup> i.e. interviewees (NE1; EF1/2/4/6–8/10/12/13; IA2/3/5; P2/3).

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).

#### 4.2.3. 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 fundamentals 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.

#### 4.2.4. 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).

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). Vermeulen et al. (2007) furthermore find that by spreading negative expectations about CCI to both concrete manufacturers and buyers, industry associations pose a formidable

barrier to market formation.

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 and 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 et al., 2012; Lechtenböhmer et al., 2015a,b; Wesseling et al., forthcoming). Hence, industry roadmaps conflict fundamentally with the academic discourse on what CCI is feasible and necessary to meet emission reduction targets.

#### 4.2.5. 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 discount. 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 realize (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).<sup>13</sup>

A successful case of public procurement of clean concrete (projectbureau Zeeweringen) indicates that the policy should be

<sup>13</sup> As in other energy-intensive processing industries, market penetration times for specialized products (like prefabricated) are much shorter (Wesseling et al., forthcoming).

able to demand cleaner concrete over time and that, in line with the literature on public procurement for innovation (Edquist and Zabala-Iturrigagoitia, 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 it has been strongly opposed and watered down by the lobby of the cement industry and others (Christensen, 2013), significantly reducing its influence. Several interviewees (EF5/6/13) indicated however that they are preparing for a more stringent EU ETS.

#### 4.2.6. 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 and 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.

#### 4.2.7. 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 focus on eco-efficiency in the use phase (Dewald and Achternbosch, 2015). Clean concrete is simply not visible to the user; “it is still grey” (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 (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<sup>14</sup> that represent established firms of different sizes at the national and European level (Christensen,

2013). 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).

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 under the EU ETS (Christensen, 2013) and by the mechanisms indicated under system function guidance of the search.

#### 4.2.8. 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.

#### 4.3. Interdependence of systemic problems: systemic lock-in

Based on the previously discussed structural-functional analysis, Fig. 3 provides an overview of the systemic problems (rectangles), the effects they have on system function (SF) performance (ovals), and how these functions may trigger, sustain or reinforce other systemic problems. The figure identifies four, differently colored, closed cycles of interdependent systemic problems. To indicate that the green, purple, red and blue cycles all feed into the lack of a CCI market, the lack of challengers to established firms' vested interests and these companies' defensive lobby (and lack of commercial CCI experimentation), these system functions and systemic problems are colored orange.<sup>15</sup> By sustaining systemic problems to CCI diffusion, these closed cycles constitute systemic lock-in.

On the demand-side, the green cycle shows how procurers of concrete are risk-averse, conservative and lack knowledge when it comes to CCI (problem, upper left in Fig. 3). This is a systemic problem because it results in negative CCI expectations (SF4), guiding the search instead to safe, conventional concrete. This behavior has been institutionalized in the routinized procurement of the highest quality concrete that complies with norm and certification committees (problem-a). In this procurement process, concrete producers are involved in a late stage (problem-b), preventing them from sharing knowledge on CCI (SF3), if they wanted to. This lack of knowledge sharing sustains the initial systemic problem of procurers lacking knowledge.

The purple cycle describes how established firms with vested interests (problem, lower right in Fig. 3) are, through their well-coordinated lobby (SF7) (reinforced by a strong sectoral culture of self-governance), able to capture norm and certification committees. These committees are very conservative; their procedures are not always compatible with more radical CCI and are very costly

<sup>14</sup> Vermeulen et al. (2007) identified 72 associations that had an interest in the concrete industry.

<sup>15</sup> The system functions and problems in light grey are not part of a closed cycle.



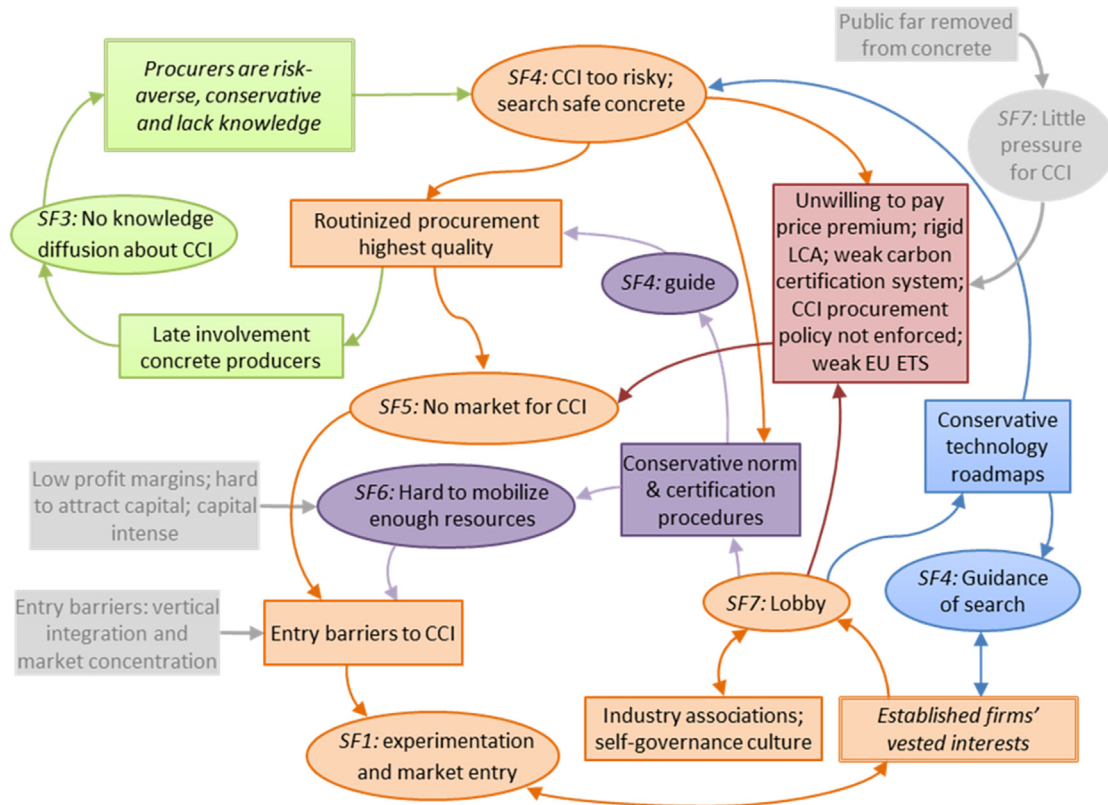


Fig. 3. Four cycles of differently colored systemic problems (rectangles) that are interdependent through their effects on system functions (ovals).

and time-consuming to comply with (problem). On the one hand, such procedures impair the mobilization of resources for innovation (SF6), which imposes barriers to entry in segments for cleaner concrete (problem); lack of experimental challengers in this segment (SF1), reinforces the position of established firms with vested interests (problem). On the other hand, by disadvantaging certain CCI, the conservative committees guide the search (SF4) of the routinized procurement (problem) away from CCI, preventing a market for CCI from emerging (SF5), posing another entry barrier to clean concrete market segments (problem) and reinforcing the position of vested interests, closing the loop of interdependent problems.

The red cycle describes how the lobby (SF7) of established cement industry's vested interests (problem), supported by well-organized industry associations (problem), opposes and waters down regulations that support or mandate CCI, like the EU ETS (problem). These regulations are important to form a market for CCI (SF5); without a market the orange interdependencies are sustained, as no challengers will overthrow vested interests and their lobby.

The blue cycle shows how the vested interests' lobby, primarily through industry associations, uses conservative technology roadmaps (problem) to consolidate and spread negative expectations, seemingly supported by the industry at large, about CCI amongst procurers (SF4), reinforcing the green cycle. The negative expectations however also guide the search of other manufacturers in the cement industry away from CCI (SF4), supporting the status quo in favor of vested interests (problem).

## 5. Conclusion and policy recommendations

This study identifies four closed cycles of interdependent

systemic problems that together constitute lock-in of the Dutch concrete SSI and explains why so few clean carbon innovations are diffusing. These problems are pervasive throughout the whole system and cover the regulatory, demand and industry side. Vested interests are found to play an important role in sustaining these systemic problems to protect the status quo. The strategically sustained systemic problems inhibit system transformation, particularly by influencing guidance of the search, entrepreneurial activities, market formation, and resources mobilization. To overcome systemic lock-in and support the diffusion of CCI, a specific sequence of policy measures is recommended below.

In the light of this special volume, this 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, which legitimizes policy interventions to mitigate the power of these vested interests.

Although this case study focused on the Netherlands, the findings on the prominence of vested interests and systemic lock-in are expected to be generalizable to other EU countries. This is not only because of the similarities in industry structure across Europe, but also because the Netherlands imports most of its cement, which suggests that the cement lobby should be less influential in inhibiting CCI to protect their vested interests than in other EU countries. Second, Dutch concrete production and consumption is relatively clean, implying that CCI are diffusing better than in other European countries. These factors suggest that vested interests and systemic lock-in may be more prominent in other European

countries than in the Netherlands.

The main contribution of this paper to the innovation systems literature lies in (re)introducing the concept of systemic lock-in, which takes place when interdependent systemic problems sustain each other through one or more closed feedback cycles, and in providing an adapted structural-function approach to concretely analyze systemic lock-in. This concept and approach enable moving beyond studying emerging TIS (Coenen and López, 2010) to include the analysis of transforming mature (sectoral and technological) innovation systems and their associated transformative systemic problems or failures (Weber and Rohracher, 2012). Such a mature innovation systems perspective is useful for comprehensively studying directional systems transformation through the development and diffusion of different types of complementary and competing innovations along the entire value chain of the focal system. This is particularly relevant for studying the sustainability transformation of energy-intensive processing industries. The concept and approach also provide handholds to study the role of established firms' vested interests in system transformation or transition and how they may strategically induce or sustain systemic problems.

### 5.1. Policy recommendations

Overcoming systemic lock-in requires policy interventions that go beyond independently solving individual systemic problems. Instead, coordination of policy measures that support innovation and pressure the regime is warranted to enable system transformation (Weber and Rohracher, 2012; Kivimaa and Kern, 2015). The findings of our analysis confirm this and suggest that such policy measures should be implemented in a specific order to prevent reverting back to a state of lock-in. An example is described below; complementary policy recommendations can be found in the PBL report (Van der Vooren et al., 2015).

First, it is important to mitigate the power of vested interests, as they reinforce many systemic problems. This can be done by for example becoming less responsive to the lobby of vested interests,<sup>16</sup> by recognizing that roadmaps may be used strategically to safeguard these interests, by developing in-house expertise to contravene lobbying and by replacing established firms with more neutral actors in norm and certification committees to ensure that their procedures become more open to CCI.

Subsequently, procurer-supplier knowledge diffusion should be facilitated to overcome the lack of knowledge on the (often public) procurement side. If the power of vested interests would not first be mitigated, the supported knowledge diffusion may be captured by these interests, resulting in negative expectations that would sustain systemic problems like conservative procurers and routinized procurement for established cements. Instead, knowledge should be diffused through multi-stakeholder roadmaps and by involving innovative suppliers earlier on in the PPI process.

Policy makers should then support market creation for CCI, which involves a willingness amongst public procurers to pay a price premium for clean concrete. Recommending public procurers to pay this premium will only be effective if they believe in the benefit of the innovation. This will only happen if their information inputs become less biased. Hence, overcoming systemic lock-in to support system transformation requires the coordinated implementation of various interlinked policy instruments.

### Acknowledgments

We thank all the interviewees for their candid responses, which enabled this paper. We want to thank the Swedish Energy Agency P38271-1 for funding this study through the GIST project, as well as PBL Netherlands Environmental Assessment Agency. We want to thank Staffan Jacobsson, Alco Kieft, Frederic Bauer and the three anonymous reviewers for their constructive comments that helped improve this paper.

### 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. *Cem. Concr. 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. <http://dx.doi.org/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. Transit.* <http://dx.doi.org/10.1016/j.eist.2015.07.003>.
- Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008. Analyzing the functional dynamics of technological innovation systems: a scheme of analysis. *Res. Policy* 37, 407–429. <http://dx.doi.org/10.1016/j.respol.2007.12.003>.
- Bijleveld, M.M., Bergsma, 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., Jacobsson, S., 1997. In search for useful public policies. In: *Technological Systems and Industrial Dynamics*. Kluwer Academic Publishers, pp. 299–316.
- CementenBeton, 2016. Betonmarkt. <http://www.cementenbeton.nl/marktinformatie/betonmarkt> (accessed 29.01.16).
- Cement, BetonCentrum, 2012. Roadmap Duurzaam Cement. <http://www.cementenbeton.nl/duurzaam-bouwen/cement-en-co2> (accessed 29.01.16).
- Christensen, A.R., 2013. Cement industry. In: Skjærseth, J.B., Eikeland, P.O. (Eds.), *Corporate Responses to EU Emissions Trading*. Ashgate, Farnham.
- Coenen, L., Benneworth, P., Truffer, B., 2012. Toward a spatial perspective on sustainability transitions. *Res. Policy* 41, 968–979. <http://dx.doi.org/10.1016/j.respol.2012.02.014>.
- Coenen, L., López, F.J., Díaz, 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. <http://dx.doi.org/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. Transit.* 1–16. <http://dx.doi.org/10.1016/j.eist.2015.10.001>.
- Edquist, C., Zabala-Iturrigagoitia, J.M., 2012. Public procurement for innovation as mission-oriented innovation policy. *Res. Policy* 41, 1757–1769. <http://dx.doi.org/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. *Energy Policy* 52, 628–638. <http://dx.doi.org/10.1016/j.enpol.2012.10.022>.
- Farla, J., Markard, J., Raven, R., Coenen, L., 2012. Sustainability transitions in the making: a closer look at actors, strategies and resources. *Technol. Forecast. Soc. Change* 79, 991–998. <http://dx.doi.org/10.1016/j.techfore.2012.02.001>.
- Fischedick, M., Roy, J., Abdel-Aziz, A., Acquaye, A., Allwood, J.M., Ceron, J.P., Geng, Y., Kheshgi, H., Lanza, A., Perczyk, D., Price, L., Santalla, E., Sheinbaum, C., Tanaka, K., 2014. Industry. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom.
- 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. <http://dx.doi.org/10.1093/joclec/nhq008>.
- 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. <http://dx.doi.org/10.1016/j.eist.2014.11.001>.
- Hasanbeigi, A., Price, L., Lin, E., 2012. Emerging energy-efficiency and CO<sub>2</sub> emission-reduction technologies for cement and concrete production: a technical review. *Renew. Sust. Energy Rev.* 16 (8), 6220–6238.
- 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. <http://dx.doi.org/10.1016/j.techfore.2008.04.013>.

<sup>16</sup> Such defensive lobbies are primarily performed by industry associations as they typically take the position of their most defensive member when it comes to technology-forcing regulation (Wesseling et al., 2015).

- 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. <http://dx.doi.org/10.1016/j.techfore.2006.03.002>.
- Huntzinger, D.N., Eatmon, T.D., 2009. A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies. *J. Clean. Prod.* 17, 668–675. <http://dx.doi.org/10.1016/j.jclepro.2008.04.007>.
- Jacobsson, S., Bergek, A., 2011. Innovation system analyses and sustainability transitions: contributions and suggestions for research. *Environ. Innov. Soc. Transit.* 1, 41–57. <http://dx.doi.org/10.1016/j.eist.2011.04.006>.
- Kebebe, E., Duncan, A.J., Klerkx, L., de Boer, I.J.M., Oosting, S.J., 2015. Understanding socio-economic and policy constraints to dairy development in Ethiopia: a coupled functional-structural innovation systems analysis. *Agric. Syst.* 141, 69–78. <http://dx.doi.org/10.1016/j.agsy.2015.09.007>.
- Kieft, A., Harmsen, R., Hekkert, M., 2016. Interactions between systemic problems in innovation systems: the case of energy-efficient houses in The Netherlands. In: *Innov. Stud. Utr.*
- Kivimaa, P., Kern, F., 2015. Creative destruction or mere niche creation? Innovation policy mixes for sustainability transitions. *Res. Policy* 02, 29. <http://dx.doi.org/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. <http://dx.doi.org/10.1016/j.technovation.2003.11.002>.
- Lamprinoupolou, 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. <http://dx.doi.org/10.1016/j.agsy.2014.05.001>.
- Lechtenböhmer, S., Nilsson, L., Åhman, M., Schneider, C., 2015a. Decarbonising the Energy Intensive Basic Materials Industry Through Electrification. *Lund Univ. Publ.*
- Lechtenböhmer, S., Schneider, C., Roche, M., Höller, S., 2015b. 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. <http://dx.doi.org/10.3390/en81011404>.
- Malerba, F., 2002. Sectoral systems of innovation and production. *Res. Policy* 31, 247–264. [http://dx.doi.org/10.1016/S0048-7333\(01\)00139-1](http://dx.doi.org/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., Truffer, B., 2006. Innovation processes in large technical systems: market liberalization as a driver for radical change? *Res. Policy* 35, 609–625. <http://dx.doi.org/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. <http://dx.doi.org/10.1080/09537320802141429>.
- Markard, J., Hekkert, M., Jacobsson, S., 2015. The technological innovation systems framework: response to six criticisms. *Environ. Innov. Soc. Transit.* 16, 76–86. <http://dx.doi.org/10.1016/j.eist.2015.07.006>.
- Narula, R., 2002. Innovation systems and “inertia” in R&D location: norwegian firms and the role of systemic lock-in. *Res. Policy* 31, 795–816. [http://dx.doi.org/10.1016/S0048-7333\(01\)00148-2](http://dx.doi.org/10.1016/S0048-7333(01)00148-2).
- Negro, S.O., Hekkert, M.P., Smits, R.E., 2007. Explaining the failure of the Dutch innovation system for biomass digestion—a functional analysis. *Energy Policy* 35, 925–938. <http://dx.doi.org/10.1016/j.enpol.2006.01.027>.
- Negro, S.O., Alkemade, F., Hekkert, M.P., 2012. Why does renewable energy diffuse so slowly? A review of innovation system problems. *Renew. Sust. Energy Rev.* 16, 3836–3846. <http://dx.doi.org/10.1016/j.rser.2012.03.043>.
- Oltra, V., Saint Jean, M., 2009. Sectoral systems of environmental innovation: an application to the French automotive industry. *Technol. Forecast. Soc. Change* 76, 567–583. <http://dx.doi.org/10.1016/j.techfore.2008.03.025>.
- 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. <http://dx.doi.org/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. <http://dx.doi.org/10.1016/j.respol.2014.11.010>.
- Phair, J.W., 2006. Green chemistry for sustainable cement production and use. *Green Chem.* 8, 763. <http://dx.doi.org/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. <http://dx.doi.org/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. <http://dx.doi.org/10.1016/j.cemconres.2011.03.019>.
- Scrivener, K.L., 2014. Options for the future of cement. *Indian Concr. J.* 11–21.
- Scrivener, K.L., Kirkpatrick, R.J., 2008. Innovation in use and research on cementitious material. *Cem. Concr. Res.* 38, 128–136. <http://dx.doi.org/10.1016/j.cemconres.2007.09.025>.
- 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. <http://dx.doi.org/10.1002/bse.1808>.
- Suurs, R.A.A., 2009. *Motors of Sustainable Innovation: towards a Theory on the Dynamics of Technological Innovation Systems*. Utr. Univ.
- Teece, D.J., Pisano, G., Shuen, A., 1997. Dynamic capabilities and strategic management. *Strateg. Manag. J.* 18, 509–533. [http://dx.doi.org/10.1002/\(SICI\)1097-0266\(199708\)18:7<509::AID-SMJ882>3.0.CO;2-Z](http://dx.doi.org/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-Wagening. J. Life Sci.* 76, 99–112. <http://dx.doi.org/10.1016/j.njas.2015.12.001>.
- Utterback, J.M., Suarez, F.F., 1993. Structure, competition, and industry. *Res. Policy* 22, 1–21.
- Van Lieshout, M., 2014. Voorbereiding convenant Concreteet 2.0 binnen de Green Deal Beton. CE Delft, Delft.
- Van Lieshout, M., 2015. Update Prioritering Handelings- Perspectieven Verduurzaming Quickscan Van 16 Door Het MVO Netwerk Colofon. 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. <http://dx.doi.org/10.1016/j.techfore.2009.08.004>.
- 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. <http://dx.doi.org/10.1177/0170840606067927>.
- VOBN-Beton, 2016. Vereniging Betonmortelfabrikanten. <http://www.vobn-beton.nl/vereniging-vobn/vereniging-betonmortelfabrikanten> (accessed 29.01.16).
- Van der Vooren, A., Reudink, M., Hanemaaijer, A., 2015. Eco-innovatie in gevestigde productieketens. In: *Een analyse van de beton- en de glastuinbouwketen*. PBL, Den Haag.
- WBCSD, 2009. *Cement Technology Roadmap 2009 Carbon Emissions Reductions up to 2050*. World Business Council for Sustainable Development.
- Weber, K.M., Rohrer, 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. <http://dx.doi.org/10.1016/j.respol.2011.10.015>.
- Wesseling, J.H., Edquist, C., 2016. Public procurement for innovation: lessons from the procurement of a navigable storm surge barrier. In: *Pap. in Innov. Stud.*
- Wesseling, J., Åhman, M., Coenen, L., Lechtenböhmer, S., Nilsson, L., Vallentin, D., Worrell, E., 2016. Decarbonizing energy-intensive processing industries: stylized facts and research agenda. In: *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. <http://dx.doi.org/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. <http://dx.doi.org/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. [http://dx.doi.org/10.1016/S0301-4215\(00\)00097-5](http://dx.doi.org/10.1016/S0301-4215(00)00097-5).