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Article

Public procurement for innovation to help meet societal challenges: a review and case study

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Abstract

Public procurement for innovation (PPI) is a powerful, underutilized demand-side innovation policy instrument. How this instrument can contribute to meeting societal challenges, which require goal-oriented transformation of socio-technical systems, remains unclear and is explored in this article. This article draws on the transitions and PPI literature to propose transformative processes to which PPI can contribute and identifies factors that determine the effectiveness of PPI in meeting societal challenges. The propositions are explored with a case study on the procurement of radically new flood barrier technology, using event history mapping analysis. The article concludes that, under certain conditions, PPI can contribute to the transformative processes of (1) the articulation of societal demands to direct challenge-driven transformation; (2) the development and production; (3) selection; and (4) the diffusion and use of new technologies to meet these societal demands. The article ends with policy recommendations on how PPI can help meet societal challenges.

Key words: innovation system; tender; water sector; infrastructure; socio-technical Transition; demand-side innovation policy

1. Introduction

Meeting grand societal challenges has gained increasing attention in the policy arena. These grand challenges differ in complexity as they may focus on one sector (e.g. energy or transport) or cut across sectors (e.g. environmental sustainability or security), and may be inspired by one or multiple, possibly interacting, societal demands like the grand challenge of 'smart, green and integrated transport' (Kuhlmann and Rip 2014). Meeting such challenges requires goal-oriented transformation of existing socio-technical (ST-) systems (Alkemade et al. 2011; Kuhlmann and Rip 2014). ST-systems comprise stable configurations of interacting actors, institutions, technology, and infrastructures, and are defined by the societal demands they fulfill, for example, water management or transportation (Geels 2004; Markard and Truffer 2008). To meet a grand challenge, one or more of these stable ST-system configurations should transform to enable fulfilling the societal demands associated with the grand challenge (Geels and Schot 2007; Kuhlmann and Rip 2014; Weber and Rohracher 2012). Hence, meeting a grand challenge goes beyond technical innovation and includes change in all dimensions of the ST-system, including also industry, policy, user preferences, science, and culture (Geels 2012).

Effectuating such transformative change to meet grand challenges is a challenge in itself and requires a well-coordinated mix of policy instruments that crosses ministerial boundaries (OECD 2015: 9) and that targets the whole ST-system (Kivimaa and Kern 2015; Kuhlmann and Rip 2014; Rogge and Reichardt 2016; Weber and Rohracher 2012). This implies moving beyond the historical supply-push orientation to include demand-side instruments, particularly for the more complex grand challenges (Boon and Edler, 2018). Although demand-side measures are increasingly implemented, research is behind in understanding how these measures help meet grand challenges (Boon and Edler, 2018).

This article contributes to this understanding by exploring how public procurement for innovation (PPI), which is a particularly powerful demand-side instrument, can support (grand) challenge-driven system transformation. PPI is 'the process by which public organizations place an order for the fulfillment of certain functions by a new product (good, service, and system) that does not yet exist, and whose development and diffusion will influence the direction and rate of technological change and other innovation processes' (Edquist and Zabala-Iturriagagoitia 2012: 1766). So far, only Edquist and Zabala-Iturriagagoitia (2012) have studied how PPI contributes to tackling grand challenges. In line with Frenken (2017), they argue that because these challenges are so grand, they can only be met by reducing them to more narrow and manageable societal challenges or missions. Edquist and Zabala-Iturriagagoitia (2012) show with a comparative case study that PPI can effectively contribute to meeting these narrower societal challenges, but exclude challenges comprised of multiple, interacting societal demands that better approach the complexity of grand challenges. They also do not identify the precise processes through and conditions under which PPI can facilitate challenge-driven systems transformation.

Building on the PPI and transitions literature, this article proposes that PPI is a policy instrument that can facilitate such transformation by triggering multiple actors of the ST-system (including government and its agencies, knowledge institutes, industries, users, and other stakeholder groups) to articulate and facilitate societal demands to direct challenge-driven transformation, and to develop, select, and diffuse new technologies to meet these demands. We explore PPI's potential to contribute to these transformative processes through an in-depth case study.

The case study focuses on a PPI project that became instrumental to the Dutch water construction sector's transformation from a ST-system revolving around dyke reinforcement to provide water safety from storm surges, to one revolving also around radically innovative flood barriers (supplied by new entrants) to meet additional societal demands related to maritime transportation, ecology, and land use (CSW 1987). This transformation was triggered by a societal challenge that arose mainly from the 1953 large-scale flooding and was manifested in the Delta Works program that mandated the procurement of several flood barriers. The societal demands that comprised the challenge relate to today's grand challenges of 'secure societies' and of 'smart, green and integrated transport' (European Comission 2016). To help meet the challenge, the focal PPI project procured a radically innovative flood barrier in the New Waterway that became an integral part of the transformed Dutch water construction sector.

The remainder of the article is structured as follows. To pinpoint the precise mechanisms by which PPI contributes to challenge-driven systems transformation, Section 2 first reviews the PPI literature to identify factors that contribute to the effectiveness of PPI in meeting societal demands that underpin societal challenges. It then proposes how and under what conditions PPI may contribute to challenge-driven system transformation. Section 3 provides a case description. Section 4 describes the different stages and processes of the PPI under study and assesses whether the propositions hold for this case. Section 5 concludes by discussing the transformative processes through which PPI can help meet societal challenges and Section 6 provides policy recommendations on how to design effective PPI.

2. PPI and challenge-driven system transformation

2.1 Important factors for effective PPI

The effectiveness with which PPI contributes to meeting one or multiple societal demands that underpin societal challenges is contingent on several factors. A review of the PPI literature identifies the following six factors.

1. The *type of PPI* is important: *direct PPI* implies that the procuring organization is also the end user of the procured innovation, or is responsible for the societal demands that are achieved through the innovation, whereas *catalytic PPI* means that the procuring agency serves merely as a catalyst, coordinator, and resource to procure innovation on behalf of the end user (Edler and Georghiou 2007; Edquist and Zabala-Iturriagagoitia 2012; Hommen and Rolfstam 2009). Furthermore, *developmental PPI* demands a completely new product that requires radical innovation, typically necessitating intense R&D efforts before implementation, whereas *adaptive PPI* requires only incremental adaptation before implementation (Edler and Georghiou 2007; Edquist and Zabala-Iturriagagoitia 2012; Hommen and Rolfstam 2009). Since meeting societal challenges often requires completely new products, developmental PPI may be more suitable.

2. *Gathering market intelligence* on what potential suppliers can be expected to deliver in terms of (different kinds of) solutions is an important initial step in the PPI process to establish the feasibility of the innovations that are intended to be procured (Edler et al. 2005; Uyarra and Flanagan 2010). To prevent privileging potential suppliers, this process should be transparent and strictly separated from the actual tender (Edler et al. 2005).

3. For the PPI to effectively meet the societal demands that constitute a societal challenge, the *articulation and specification of* these *societal demands into PPI goals* at the early stage of PPI is crucial. Boon and Edler (2018) distinguish between user-led societal demands, which are articulated by users, citizens, or activist groups, and policy-led societal demands that emerge through political processes. Policymakers may specify these demands into policy goals that are pursued with policy measures, either directly (in the case of direct PPI) or by influencing consumer behavior (catalytic PPI). Edler et al. (2005: 9) conclude that 'one of the greatest challenges in the early phase of [the PPI process]... is to reconcile the expectations, needs and limitations of a large number of users'. By involving users at an early stage, policymakers may tap into their creativity and resources, and by specifying user-led demands into PPI goals, they may obtain legitimacy for the PPI process and for the procured innovation, which eases implementation problems (Boon and Edler, 2018).

4. The *specification of functional requirements* should provide the directionality to the innovation process needed to meet the societal demands specified in the PPI goals. For this purpose, a balance should be found in formulating the functional requirements narrowly enough to effectively direct the innovation process, but broadly enough to stimulate creativity and technological variety (Edler et al. 2005; Edquist 2015; Edquist and Zabala 2012). Uyarra et al. (2014: 631) for example identify 'the use of over-specified tenders as opposed to outcome based specifications' as a major barrier to PPI.

5. It is crucial that the procuring agencies *possess or acquire the necessary expertise* to conduct the PPI. Operational expertise is necessary to identify societal demands, translate them into PPI goals, specify the functional requirements to meet these goals, assess the quality of the supplied innovations and manage the overall PPI process (Edler et al. 2005; Uyarra et al. 2014; Boon and Edler, 2018). Expertise can be acquired externally, for example, when commissioning feasibility studies on potential innovations to gather market intelligence or to evaluate competing designs (Edler et al. 2005).

6. *Finding a balance between cooperation and competition* is also important. Cooperation amongst procurers and (consortia of) suppliers stimulates learning by interacting but may reduce technological variety as well as competition between suppliers (Edler et al. 2005; Edquist and Zabala-Iturriagagoitia 2012; Hommen and Rolfstam 2009). Competition between suppliers, in turn, triggers them to commit more resources to their innovation process. Uyarra et al. (2014) identify the lack of procurer–supplier interaction as a major problem for PPI.

2.2 Challenge-driven systems transformation through PPI

Meeting grand societal challenges involves significant technical and institutional changes and, therefore, requires challenge-driven transformation of one or more ST-systems (Alkemade et al. 2011; Kuhlmann and Rip 2014). Borrás and Edler (2014: 11) define ST- and innovation systems alike, as 'articulated ensembles of social and technical elements which interact with each other in distinct ways, are distinguishable from their environment, have developed specific forms of collective knowledge production, knowledge utilization and innovation, and which are oriented towards specific purposes in society and economy'.

This article proposes that PPI is a policy instrument that, under certain conditions, can contribute to challenge-driven ST-systems transformation, by triggering multiple actors of that system (including government and its agencies, knowledge institutes, industries, users, and other stakeholder groups) to engage in four generic transformative processes: (1) articulating and facilitating societal demands to direct challenge-driven transformation; (2) developing and producing new technologies that enable meeting these societal demands; (3) selecting the technologies that best enable meeting these demands; and (4) diffusing and adequately using the selected technologies to meet the demands that underpin societal challenges.

To assess the impact of PPI on these transformative processes, we turn to the transitions literature. Various frameworks have been developed to study the development or change of ST-systems in the context of transitions, including Strategic Niche Management, the Multi-Level Perspective, Transitions Management, and Technological Innovation Systems (TIS). Of these frameworks, TIS and its associated system functions approach is the most developed in measuring the key ST- innovation processes (i.e. system functions) that underpin the development, production, and diffusion of new technology within a ST-system (Coenen and Díaz López 2010; Markard and Truffer 2008). Another term for 'the system functions approach' is 'the systems activities approach' (Borrás and Edquist 2017).[1] The system functions approach, however, omits challenge-driven transformative processes that go beyond the technology-specific level, such as articulating and facilitating of (new) societal demands to direct transformation, and selecting between competing technologies (Borrás and Edler 2014; Kivimaa and Kern 2015; Markard and Truffer 2008; Weber and Rohracher 2012; Wesseling and Van der Vooren 2017). Therefore, we build on the system functions approach to assess the impact of PPI on technology development, production, and diffusion, but use the PPI and transitions literatures to operationalize the 'articulation and facilitation of societal demands to direct transformation' and 'the selection between technologies'. Below we discuss how and under what conditions PPI may contribute to these transformative processes, and we develop propositions that are to be explored in the case study.

2.2.1 Articulate and facilitate societal demands to direct transformation

Systems transformations are directed by the societal challenges and underlying societal demands that drive them. To meet these challenges effectively, policymakers should inventory all the societal demands their intended policy measure (e.g. PPI) can help meet in an integrated manner. Identifying new societal demands is important to redefine challenges and redirect system transformation. Weber and Rohracher (2012) label this inability to identify societal demands a transformational system failure related to demand articulation. Supporting the identification and articulation of societal demands requires proactive communication with different societal actors, for example, through multistakeholder meetings.

PPI may facilitate this transformational process by stimulating different stakeholders to articulate their demands before the tendering process, and specifying these demands into the goals that direct the PPI process (Edler et al. 2005) (see Section 2.1). Under the condition that PPI successfully engages in these processes, we propose that:

Proposition 1: PPI can contribute to challenge-driven transformative change by facilitating the articulation and facilitation of societal demands to direct systems transformation.

2.2.2 Develop and produce new technologies that help meet the societal demands

New technologies and associated institutional changes are often necessary to meet societal challenges, as established technologies typically do not suffice. The replacement of fossil fuel-based technologies with renewable energy and zero emission vehicle technologies are, for example, important solutions to help meet long-term sustainability demands (Dincer 2000; Uherek et al. 2010). As described by the system functions approach, the development and production of new technologies requires several key innovation processes (Bergek et al. 2008; Hekkert et al. 2007). First, it requires entrepreneurial experimentation with new designs, applications, services, and organizational innovations that better meet the changing societal demands. Such experimentation takes place in, for example, pilot projects that enable learning by doing. Second, it requires knowledge development, which refers to learning by searching (e.g. through R&D), by interacting and by using and is important to design and further develop technologies so that they better meet societal demands ((Bergek et al. 2008; Hekkert et al. 2007). Third, it requires knowledge diffusion to cooperatively develop technology (supplier–supplier interaction) and to assess the demand for emerging technologies (supplier–buyer interaction) (Bergek et al. 2008; Hekkert et al. 2007). Fourth, it requires mobilization of significant financial, human, and other resources (Bergek et al. 2008; Hekkert et al. 2007). For industry to commit to the development and production of new technologies requires a change in corporate innovation strategies.

For PPI to trigger industry to allocate their resources to the development and production of new technology, the incentive (i.e. the procurement demand) should be sufficiently large. As described in Section 2.1, PPI is particularly effective in this transformation process when it finds a balance between cooperation, to facilitate learning by interacting, and competition, to trigger industry resource commitment. So under the above two conditions, we propose that:

Proposition 2: PPI can contribute to challenge-driven transformative change by facilitating the development and production of new technologies that help meet the challenge.

2.2.3 Select the technologies that best help meet the societal demands

Various technologies may help meet a certain societal challenge or demand. There are, for example, several renewable energy and zero emission vehicle technologies to help meet sustainability targets in these sectors. Although technological diversity is important to prevent early lock in on a suboptimal technology, spreading limited resources too thinly may stall the transformation process. Therefore, it is important to, at the right stage, select one or more the technologies that best help meet the societal demands. This selection process helps consolidate the direction for change within a system. Weber and Rohracher (2012) label the lack of directionality as a transformational system failure.

PPI can be a highly effective tool for this selection process, although its success is contingent on several conditions (see Section 2.1). First, pre-PPI market intelligence should inform procurers about the potential of innovation to determine if PPI will commence. Second, (successive rounds of) functional requirements should direct the innovation process by industry and provide a basis for selecting the winning technology. Third, there should be substantial expertise within the PPI organization to manage its processes, as well as knowledge development and diffusion to substantiate the selection of the best technology design. As long as these conditions are met, we propose that:

Proposition 3: PPI can contribute to challenge-driven transformative change by facilitating the selection of the technology(s) that best help meet the challenge.

2.2.4 Diffuse and utilize the technologies that best help meet the societal demands

After developing and selecting the technologies that best help meet societal demands it is important that these technologies diffuse throughout society and are used as intended. Diffusion, interpreted as implementation and upscaling, of these new technologies is, however, often impaired by their inferior performance characteristics (Foxon and Pearson 2008; Weber and Rohracher 2012) and can be hampered by industry resistance and a mismatch with existing regulations (Geels 2014; Wesseling and Van der Vooren 2017). Policy intervention can help form markets and support the legitimacy and diffusion of these technologies; PPI has been shown to be highly effective for market creation (Edler et al. 2005; Edquist and Zabala-Iturriagagoitia 2012). The system functions approach underlines that market formation and overcoming resistance or creating legitimacy are key to technology diffusion (Bergek et al. 2008; Hekkert et al. 2007).

Furthermore, correct use is not a given; Ligterink and Smokers (2015) have, for example, shown that plug-in hybrid vehicles are not used in the sustainable way for which they were designed. For direct PPI, correct use of the innovation and the associated necessary behavioral changes can be easily governed top-down, as the procuring agency is the end user of or responsible for the innovation. However, with catalytic PPI, the success of diffusion and end use depends on the procuring agency's ability to stimulate (catalyze) further adoption and use by society; this may require complementary demand-pull policies such as tax incentives or rebates. So, depending on the type of PPI, we propose that:

Proposition 4: PPI can contribute to challenge-driven transformative change by facilitating the diffusion and utilization of the technology(s) that best help meet the challenge.

3. Methods

To determine if PPI is a potentially useful tool for mitigating societal challenges, we explore whether the previously identified propositions hold for the specific case at hand, using an in-depth case study approach. More research, particularly through surveys and systematic case comparisons, will be required to actually test the empirical validity of these propositions. However, with the exception of one survey on procurement carried out by Georghiou et al. (2014) and Uyarra et al. (2014), empirical analyses of PPI are so far limited to case studies in various sectors and countries, while more systematic analyses are lacking (Edler et al. 2005; Flanagan et al. 2011; Hommen and Rolfstam 2009; Uyarra and Flanagan 2010). Hence, the PPI case studies that are conducted need to use systematic approaches to data collection and analysis to enable comparisons and determine under what conditions the proposed benefits to challenge-driven system transformation hold.

The following case study employs such a systematic approach, that is, history event mapping analysis, to capture the developments and causal mechanisms of the PPI process and analyze how it benefits challenge-driven transformation. The approach enables the capture of dynamic patterns of innovation activities and has been used to study innovation processes at both the micro (Van de Ven et al. 1999) and meso level, that is, through system functions (Hekkert et al. 2007). This makes the approach a useful tool to study how the PPI process contributes to transformative processes. These processes are identified and assessed using the operationalization scheme in Table 1. This operationalization scheme combines the measures from the system functions approach (Bergek et al. 2008; Hekkert et al. 2007) to operationalize technology development, production, and diffusion and the measures from the PPI and transitions literature (e.g. Edler et al. (2005); Georghiou et al. (2014); Weber and Rohracher (2012)) to operationalize particularly societal demand articulation and facilitation, and technology selection.

Our database is comprised of the public agency's extensive documentation of the PPI process and of complementary technical studies and reports. To triangulate these data and collect data on processes not captured by formal documents, interviews with eleven stakeholders were conducted. The interviewees cover all relevant stakeholders, including the project leaders and managers of the PPI project, throughout every stage of the PPI and from both the public (7) and private side (4). This article builds on a larger report, that also includes the list of interviewees; please consult Wesseling et al. (2010) for more information.

We structure the analysis by the various stages and processes of the PPI, highlighting the factors that contribute to the effectiveness of PPI and exploring the validity of the specified propositions for this specific case.

3.1 Case study description

The focal PPI project was instrumental to the challenge-driven transformation of the Dutch water construction sector, which involved change in all the ST-system dimensions defined by Geels (2012). The *technical dimension* changed from an exclusive focus on dyke reinforcement technology toward one relying also on radically innovative flood barriers. The design that won the focal PPI comprised two pivoting steel floating sector gates. It was built over the period 1987–97; it was new to the world, cost 960 million guilders (436 million euro's) and was called the Maeslant barrier (VenW 1998). The only similar design is the St. Petersburg barrier built in 2010 (Dircke et al. 2012; Hunter 2012), meaning that the catalytic lead user role that public agencies can play through PPI (Edler and Georghiou 2007) is limited for this case.

The major trigger for the systems transformation was the 1953 flooding, which resulted in the Delta Works program that mandated the procurement of several flood barriers procured in different projects. Particularly in the focal PPI, the system's *policy dimension* changed from focusing on providing only water safety from storm surges, toward also meeting additional societal demands related to maritime transportation, ecology, and land use (CSW 1987).

Our analysis indicated that this change required an accompanying change in the system's *science dimension* as the new technology and the meeting of these multiple policy goals required integration

Table 1. Operationalization scheme of transformative processes to which PPI can contribute.

Transformative process	Important system functions	Operationalization
Articulate and facilitate societal demands to direct transformation	Relates to guidance of the search, but by multiple societal demands	Multi-stakeholder meetings; voiced societal demands; specification of societal demands into policy goals
Develop new technologies to help meet societal demands	Entrepreneurial activities; knowledge development and diffusion; guidance of search within technology-specific system	New designs and pilot projects + learning by doing; R&D; diffusion of needs from PPI org. to industry; cooperative development
Select the technologies that best help meet societal demands	Relates to (a) guidance of the search, but between technologies; (b) knowledge development and diffusion for informed decision-making	Market intelligence; functional requirements for procurement; studies to inform selection process; knowledge diffusion from Industry to PPI org. to learn about innovation characteristics
Diffuse/utilize technologies to meet societal demands	Market formation; creation of legitimacy	Size of procured demand (and potential catalytic effects); procedures in place for effective use; and legitimacy for the procured innovation and procurement process, including resistance overcome
All processes	Resources mobilization	Allocated financial, human, and other resources

of several scientific disciplines (e.g. hydrology, engineering, geology, and maritime ecology). It also required a change in the ST-system's *industry dimension*, as consortia comprising new, innovative firms with different expertise entered the sector to provide these novel technologies. Finally, the *cultural dimension* changed due to shifting societal values regarding water safety and other demands (CSW 1987).

Since this PPI was part of a larger Dutch water safety program that fell under the prime responsibility of a single public agency, and because the PPI aimed for the procurement of a radically innovative flood barrier, this case classifies as a form of direct, developmental PPI.

4. Analysis

The analysis of the public procurement for a radically innovative flood barrier has been structured by the various stages of the PPI process summarized in Fig. 1. These stages include emergence of societal demands and exploration of solutions; initiation of the PPI; design and selection of solutions; implementation of the winning solution; and finalization of the PPI. A description of these stages and how they relate to the factors that influence the effectiveness of the PPI process is provided below. The analysis also illustrates how the PPI project supports the previously identified processes of challenge-driven transformative change.

4.1 Emergence of societal demands and exploration of solutions

The *emergence of* several *societal demands (Step 1, Fig. 1)* led to the public procurement of a flood barrier in the New Waterway. First, a flooding in 1953 resulted in a policy-led demand for water safety in the Netherlands that was initially[2] to be met with the conventional solution of dyke reinforcement. However, various stakeholders protested against this solution when new studies found that, due to rising sea levels caused by climate change, the dykes needed to be higher than expected (Van Oorschot and Pruijssers 1995). They argued that this would result in extensive destruction of private properties and natural and cultural heritage, and that it would damage economic growth (VenW and BMK 1995). Furthermore, the Rotterdam municipality demanded that solutions would not hamper maritime transport as this would reduce the economic competitiveness of their harbor (CSW 1987), while the national government wanted a solution that was cost-efficient and cost-efficiently procured. Together with the policy-led ecology requirements of large infrastructural projects, these interacting societal demands closely resemble the different aspects of the European Commission's grand challenges of (1) 'secure societies', which includes the prevention and mitigation of flooding, and of (2) 'smart, green and integrated transport', which aims to 'boost the competitiveness of the European transport industries and achieve a European transport system that is resource-efficient, climate-and-environmentally-friendly, safe and seamless for the benefit of all citizens, the economy and society' (EC 2016: 1). The proactive articulation of these different stakeholders' societal demands legitimized PPI to find a solution better than dyke reinforcement.

In terms of *market intelligence (Step 2, Fig. 1)*, at least five studies had been commissioned between 1954 and 1987 to explore the feasibility and costs of a flood barrier as an alternative to dyke reinforcement. Although initial studies deemed a flood barrier too costly or infeasible, they became more positive as experience with other flood barrier technologies increased through other parts of the Delta works program (Interviewees 2, 6; Smit-Kroes 1988). Eventually, a series of three studies convinced the national government that the market possessed the expertise to provide a flood barrier that complied with the needs of the different stakeholders.

4.2 Initiation of the PPI

To oversee the PPI, an extensive *project organization was set up (Step 3)*, comprising six workgroups, a coordination group, a steering group, a test group, and a PPI committee that reported to the minister (CSW 1987; CSW and RWS 1988). These groups comprised experts from different research institutes and public agencies and were responsible for assessing and selecting the supplied designs; for making sure the societal demands were met; for supporting the development of the winning design into a construction design; and for commissioning external studies. The PPI organization commissioned more than twenty studies to seven different (hydrological, geological, and engineering) research institutes to validate and complement the consortia's designs. Throughout the entire PPI at least sixty complementary studies were performed by over fifteen external organizations, indicating that the PPI had triggered substantial knowledge creation and diffusion by and between different actors to support technology development, production, and selection.

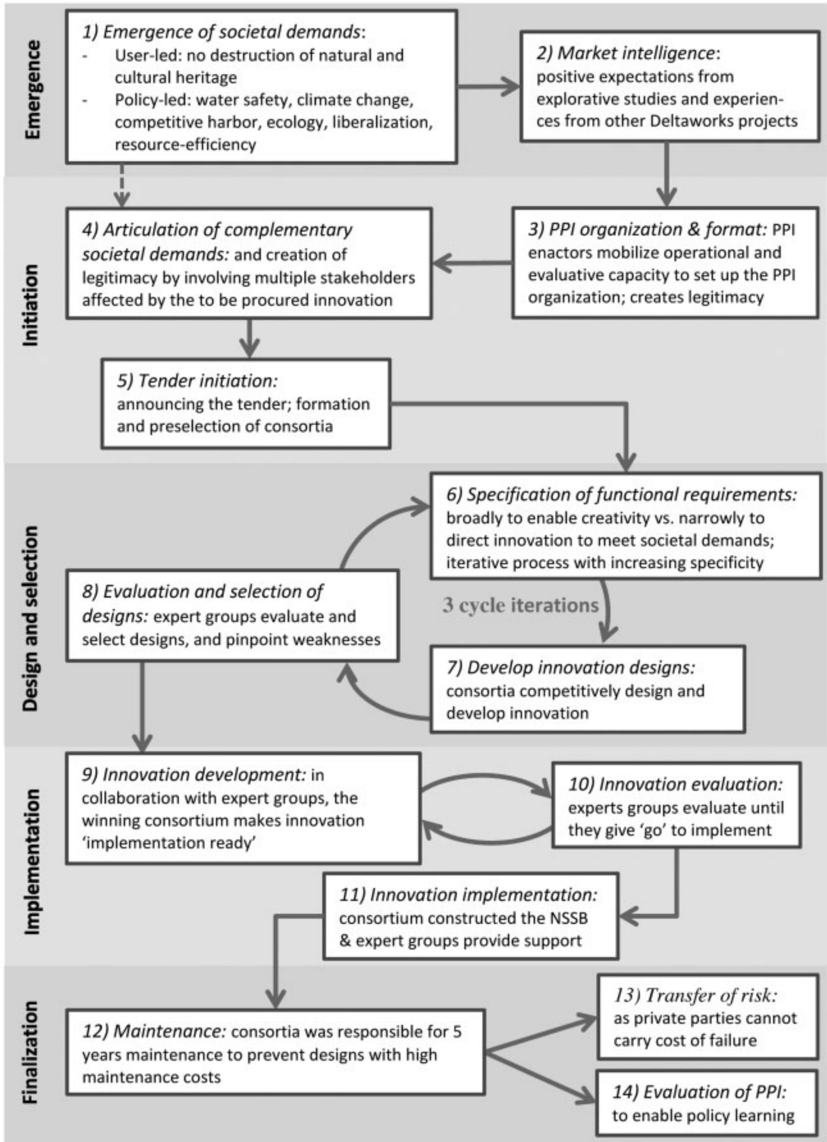

Figure 1. Overview of the stages and events that characterize the focal PPI project.

Overseeing these studies required extensive and broad knowledge of the PPI organization; this expertise served to shift the consortia's competitive focus from cost to more quality-oriented (Interviewees 3, 4), which is particularly important when the costs of failure of the innovation, which would result in flooding, are disproportionally high. To ensure resource-efficiency, the PPI organization had to justify the expenses of the PPI process to the minister, who reported to the Dutch parliament. Finally, a commission for environmental effects was instated as part of the broader PPI organization to identify and mitigate environmental concerns. This well-functioning PPI organization created and coordinated a dedicated network of actors to mobilize the resources and expertise that is necessary to monitor, codevelop, evaluate, and select amongst the competing innovation designs.

To meet the national demand of low public costs and to activate the market's innovative potential at an early stage, the PPI initiators appointed by the minister selected a *tender format (Step 3)* in which the market would design, construct, and maintain the innovation. Although this was consistent with a larger trend of liberalization in the water construction sector, it resulted in strong resistance from the public agency that would have normally been responsible for the innovation's design. This resistance was resolved through top-down pressure and the deal that the public agency would make a so called 'shadow design' that would be constructed if the consortia would not provide high-quality solutions (Interviewees 2–8). Activating the market not only for the innovation's construction and maintenance, but also for its design brought in significant resources, expertise, and creativity to explore and develop different technological trajectories at the same time; this design-construct-maintain tender has become the standard in most infrastructural projects. This tender format, in coordination with the well-functioning evaluation and selection system provided a powerful and structured innovation development and selection subsystem.

The relevant stakeholders, that is nature, cultural and local citizen interest groups and the Rotterdam municipality, had, in this case, already articulated their societal demands before the PPI was initiated. Nevertheless, by enabling these stakeholders to *articulate* their personal interests within the larger set of *societal demands (Step 4)*, by specifying these demands into PPI goals and by informing stakeholders about the progress of the PPI, the PPI organization was able to create legitimacy for the PPI process and its output (Interviewees 2, 7; CSW 1987). This legitimacy brought a stop to the stakeholders' opposition to solutions initiated before the PPI; instead the stakeholder participated proactively in the PPI process.[3]

When the goal of the PPI was clear, the *tender was initiated (Step 5)* and published nationally. Triggered by the large demand and its symbolic value that would greatly benefit the winner's reputation (Interviewees 8–11), thirty-three interested suppliers formed six consortia to complement each other's expertise. Based on preselection criteria that included financial means, production capacity, and experience, one consortium was precluded from the tender (Interviewee 8).

4.3 Design and selection stage

The design and selection stage included three iterations of *formulating increasingly specific functional requirements (Step 6)*, further *developing the innovation designs (Step 7)*, and *evaluating and selecting these designs (Step 8)*. First, the PPI organization translated the societal demands of water safety, maritime transportation, and land use into very basic functional requirements that were included in the tender contract to guide the innovation process of the supplying consortia and to provide grounds for the technology selection process.[4]

The functional requirements constituted an unprecedentedly advanced demand that made existing flood barrier designs technically insufficient (Arcadis 2006). The functional requirements' initial broad formulation facilitated creativity and enabled a broad range of solutions. Because, the public agency was afraid that the consortia's solutions would converge as a result of knowledge sharing, and to stimulate competition, they prohibited interaction between the PPI organization and the consortia (Interviewees 3, 4, 7, 8). During the first three-month design period, the five competing consortia came up with six very different designs (CSW and RWS 1988).

Evaluation, however, indicated that too little information on the feasibility of the radically new solutions was available to make a substantiated selection. Therefore, the PPI organization introduced another selection round, for which they used externally commissioned studies to set more specific functional requirements that also included the other societal demands and to pose detailed questions about the feasibility of the consortia's designs (CSW 1987; CSW and RWS 1988). The consortia tested their designs several times in the Dutch hydrological laboratory to prove their feasibility (Interviewees 8, 9, 11). This iterative process occurred once more after the second selection round. These iterations enabled the PPI organization to balance, on the one hand, broad initial requirements to facilitate innovation diversity and then increasingly specify these requirements to, on the other hand, better steer the innovation process. This balance enabled the selection of the design that best met the specified PPI goals[5] (Interviewees 2–6).

4.4 Implementation stage

The winning consortium (BMK) spent two years to *make their design implementation-ready (Step 9)* and seven years to *construct (Step 11)* the navigable barrier which opened in 1997. This implementation stage was characterized by strong cooperation between the consortium and the expert groups of the PPI organization, allowing both parties to complement each other's expertise and facilitating interactive learning (Interviewees 3, 4, 7, 8). While the consortium made their design implementation-ready, the PPI organization was responsible for providing technical knowledge, *evaluating the design (Step 10)*, posing critical questions, and for giving the 'go' to build when deemed feasible (Interviewees 6, 8). Together these actors commissioned numerous technical studies from expert organizations.

Hence, the overall PPI format seems to exploit a fruitful balance between (1) stimulating competition during the early stages to enhance technological variety and mobilize more resources from the supply side and (2) stimulating procurer–supplier cooperation during the later stages to optimize further development of the selected solution when diversity was less important. Due to a lack of government budget for the procured innovation, one mistake was made during implementation when the minister, against expert opinions, demanded a hasty cost cut in the barrier's design, which made the barrier unstable and resulted in significant delays and cost increases (Interviewees 3, 4, 8, 9).

4.5 Finalization stage

As the technology came into use, the PPI organization negotiated the closing frequencies of the barrier to find a trade-off between the competing societal demands of water safety and enhanced maritime transportation, in which stakeholders had different interests. The tender contract specified that the consortium had to carry the cost of *maintenance (Step 12)* during the first five years to discourage designs with high maintenance costs (Van Oorschot and Pruijssers 1995). After this period, the government had to *assume responsibility (Step 13)* for the flood barrier because its risk of failing cannot be carried by the private supplier and because private actors have a cost-cutting orientation that is incompatible with such risk (Interviewees 3, 4). Overall, the *PPI was evaluated (Step 14)* as a success because it met the societal demands it had set out to achieve (Interviewees 2–6).

4.6 Effect on transformative processes

The analysis shows that although stakeholders had already raised societal demands before the initiation of the PPI process, the PPI organization brought together different societal actors to articulate their demands and help legitimize the PPI's transformative process. Subsequently, the articulated societal demands were specified as goals that would direct the PPI process in terms of technology development, production, selection, and diffusion. Hence, supported by these factors, we find that *Proposition 1: PPI can contribute to challenge-driven transformative change by facilitating the articulation and facilitation of societal demands to direct system transformation* holds true for this case study.

The PPI's demand was of sufficient size and important symbolic value to trigger five consortia to develop and submit six new technology designs that were developed over time. The focal PPI also struck a good balance between (1) competition to trigger market parties to commit resources and stimulate technological divergence, and (2) cooperation to combine expertise and codevelop innovations at later stages of the PPI process. Due to these conditions, the case study supports *Proposition 2: PPI can contribute to challenge-driven transformative change by facilitating the development and production of new technologies that help meet the challenge.*

The PPI's functional requirements were initially formulated broadly to enable technological divergence, but became increasingly narrow over successive technology selection stages to guide the innovation process toward solutions that would help meet the societal challenge. The substantial operational expertise of the PPI organization and the extensive knowledge flows it facilitated (including market intelligence) were crucial to enable this selection and guidance process. Due to these factors, the case study supports *Proposition 3: PPI can contribute to challenge-driven transformative change by facilitating the selection of the technology(s) that best help meet the challenge.*

The catalytic diffusion benefit of this case of direct PPI is limited as the PPIs winning technology was replicated only once (Dircke et al. 2012; Hunter 2012). The PPI organization helped negotiate between stakeholders the end use of the technology, which meant a traded-off between different societal demands. Due to these factors and despite the limited catalytic effect, the case study supports *Proposition 4: PPI can contribute to challenge-driven transformative change by facilitating the diffusion and utilization of the technology(s) that best help meet the challenge.*

5. Conclusions and discussion

This study brings together the PPI and transitions literatures to formulate propositions on how PPI can contribute to meeting societal challenges and to explore factors that influence its success in doing so. We explored the validity of these propositions with an in-depth, historical case study of direct developmental PPI that was instrumental to the challenge-driven transformation of the Dutch water construction sector. These propositions, which held true for this specific case study, suggest that PPI can help meet societal challenges by facilitating four transformative processes:

1. PPI can contribute to challenge-driven transformative change by facilitating the articulation and facilitation of societal demands to direct system transformation.
2. PPI can contribute to challenge-driven transformative change by facilitating the development and production of new technologies that help meet the challenge.
3. PPI can contribute to challenge-driven transformative change by facilitating the selection of the technology(s) that best help meet the challenge.
4. PPI can contribute to challenge-driven transformative change by facilitating the diffusion and utilization of the technology(s) that best help meet the challenge.

The effectiveness of PPI in meeting societal challenges is, however, contingent on several factors including, but not limited to, the type of PPI; collection of market intelligence; use of multistakeholder meetings to identify societal demands; specification of functional requirements (as opposed to specific requirements); operational expertise; and balancing competition amongst and cooperation with suppliers; and also regulatory issues could inhibit PPI.[6] If these factors are favorable, as in this specific case study, PPI can be a powerful policy tool that has the potential to stimulate challenge-driven ST-systems change. These factors and the validity of our propositions should be further studied by systematically assessing and comparing larger numbers of PPI. Another relevant venue for further research is to analyze how different types of PPI fit within broader mixes of policy instruments directed at meeting societal challenges (Rogge and Reichardt 2016).

Linking to the ST- and innovation systems literature, the studied case of developmental PPI could be perceived as a temporary, small-scale and demand-driven or mission-oriented innovation system where new and existing actors of different types are brought together in a reconfigured network, not only guided by a combination of mostly existing but also new institutions, with the goal to develop, select, and diffuse new technologies that meet the societal demands driving the temporary innovation system.

One important implication of societal challenges is that they typically demand more than technological fixes and require comprehensive institutional changes (Frenken 2017; Kuhlmann and Rip 2014)—not only regulatory, but also normative and cultural-cognitive changes (Scott 2013). The societal challenge studied in this article could, however, largely be met with a technological solution, that is, a flood barrier. Although this innovation required changes in its ST- system for it to emerge, it did not necessitate wider consumer behavioral changes. It, therefore, resembles more a technological fix than the solutions to other challenges, such as reducing the prevalence of obesity (which requires e.g. different consumption patterns and physical exercise) and the prevention of traffic accidents (which benefits from e.g. alcohol prevention and better driving lessons) (Frenken 2017). The effect of PPI on the wider institutional changes needed to meet many societal challenges and the governance issues involved remains largely unexplored and constitutes an important venue for identifying the limits of PPI's contribution to meeting societal challenges.

A major drawback of transition studies is its lack of clearly operationalized transition processes. This complicates the assessment of policy instruments' transformative potential. By combining and building on earlier indicators across transition and PPI literatures, this study provides another step toward operationalizing the transformative processes to which policy can contribute. The literature on transitions policy would benefit from continuing this trend of operationalization.

6. Policy recommendations

Based on the case study findings and building on the factors that literature indicates make for effective PPI (indicated below in bolt), we provide policy recommendations on how PPI can help support challenge-driven systems transformation.

As a first step, to facilitate efficient *market intelligence*, it is important that the relevant societal demands are inventoried and that they guide the feasibility studies for the innovations that are to be procured.

Subsequently, and before initiating the PPI, it is important to set up a capable project organization. First, this organization should involve stakeholders to *articulate* their potentially latent or unspoken *societal demands*, so that not only policy-led, but also user-led demands can be specified into functional requirements. Even when these societal demands are apparent, multistakeholder involvement will generate legitimacy for the PPI process and its output.

Second, to facilitate the PPI process of developing, evaluating, selecting, and implementing the most desirable solution and to coordinate the knowledge flows between suppliers, stakeholders, procurers, and external experts, the PPI organization should have in-depth and multidisciplinary *expertise*. It is important that procuring organizations develop such expertise in-house as external private organizations may have different priorities and risk perceptions.

Alternatively, to enhance resource-efficiency and due to the enormous volume of public procurement—about 20 per cent of the European Union's Gross Domestic Product (Kahlenborn et al. 2010)—it may be worthwhile to create a separate (national) public organization that can offer procuring organizations and potential suppliers advice on matters of PPI.

The public demand represented by the PPI should be large enough for suppliers to commit sufficient resources to the process of developing and testing new innovation designs; PPI's ability to guide this innovation process through the *formulation of functional requirements* and to select between competing designs is what makes it such a powerful societal challenge instrument. It is important for policymakers to anticipate that during developmental PPI, not enough information may be available to select a winning design after one selection stage. They should, therefore, include multiple specification and selection stages in the design of the developmental PPI. During the first selection stage, functional requirements should be broad to stimulate creativity and enable competition within a wide range of solutions. During the subsequent stages, functional requirements should iteratively become increasingly specific, using knowledge that is developed in response and parallel to the solutions proposed by the consortia, to facilitate further development. This combination enables the most informed selection of the most desirable solution.

Finally, the implementation stage shows that uninformed intervention by politicians in the PPI process can be damaging to its outcome and that technical expertise should, therefore, take precedence over politics when it comes to making technical decisions. Finding a *balance between driving competition* amongst suppliers to facilitate technological variety, *and collaborating* with suppliers to complement expertise and facilitate learning by interacting, is important for policymakers to mobilize resources and expertise within the PPI. A fruitful balance may be struck by facilitating competition during the early design stages when technological variety is most important and by facilitating cooperation during later stages when selected design(s) need to be further developed and implemented.

Notes

1. This has to do with different choices of terms to denote what happens in innovation systems or determinants of innovation processes. Edquist (2005, 2011) prefers 'activities' in innovation systems while Bergek et al. (2008) as well as Hekkert et al. (2007) prefer 'functions'.
2. The New Waterway project was initially not planned to be part of the Delta Works program that mandated various other flood barriers in response to the 1953 flooding.
3. These stakeholders were, however, allowed no voice in the tenders' selection process, since such a decision requires extensive technical knowledge (Interviewee 2).
4. The requirements included (1) a reduction of the normative high water levels of 1.6 m by Rotterdam and 0.4–0.6 m by Dordrecht; (2) that all innovation designs must apply to the indicated 6 km region of the New Waterway; (3) a passage breadth of 360 m; (4) an unlimited passage height; (5) a threshold depth of −17.0 m below sea level (CSW 1987).
5. As it became clearer that the societal solutions would be met, cost became an increasingly important selection criterion.
6. Both regulatory issues relating to the innovation that is to be procured (inhibiting, for example, its implementation) as well as regulatory issues relating to the procurement process (Edquist and Borrás 2017).

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