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Unpacking transnational industry legitimacy dynamics, windows of opportunity, and latecomers' catch-up in complex product systems

Kiho Kwak^a, Hyungseok (David) Yoon^{b,*}

^a Graduate School of Management of Technology, Pukyong National University, Busan, South Korea

^b Leeds University Business School, University of Leeds, Leeds, United Kingdom

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ABSTRACT

This paper posits that the combination of changes in a forerunner's industry legitimacy and a latecomer's efforts to endogenise windows of opportunity allows the latecomer to evolve from a turnkey importer to a global exporter. Our theoretical assertions are supported by analysing Korea as a latecomer in the nuclear power industry. We show that both an increase and a decrease in a forerunner's industry legitimacy provides exogenous windows of opportunity for the latecomer to access a forerunner's knowledge base. In particular, the decrease in a forerunner's industry legitimacy provides a critical opportunity for the latecomer to acquire core technology. In addition, our analysis shows some interesting findings on the latecomer's endogenisation of windows of opportunity through the lens of technological innovation systems. This study advances a more fine-grained view on catch-up theory by shedding new light on the implications of transnational industry legitimacy dynamics and windows of opportunity for a latecomer's catch-up in complex product systems.

1. Introduction

Complex product systems (CoPS) are considered socio-technical systems (Geels, 2004, 2006; Gil et al., 2012; Walker, 2000) that are the deliverables of very costly and technology-intensive mega-projects (Hobday et al., 2005). Because of the technological complexity of CoPS and high entry barriers set by incumbents (Davies and Brady, 2000; Park, 2012), it is challenging for latecomers to enter a CoPS industry. Despite the challenges, disruptive changes in a forerunner's industry legitimacy that cause industrial crisis can create exogenous windows of opportunity for latecomers to acquire and absorb technologies released by the forerunners (Mathews, 2005; Lee and Mathews, 2012; Lee and Malerba, 2017). Surprisingly, however, prior studies on CoPS have not paid sufficient attention to the implications of transnational legitimacy dynamics such as an exogenous window for latecomers to catch up.

In addition to exogenous windows of opportunity derived from the changes in forerunners' industry legitimacy to which latecomers can merely or passively 'respond' in a transnational context (Yap and Truffer, 2019), we also investigate how latecomers in a domestic context actively endogenise windows of opportunity by considering the six core functions of technological innovation systems (TIS) for successful industry formation and catch-up (Carlsson and Stankiewicz, 1991). The functions are knowledge development, entrepreneurial experimentation, guidance of a search, legitimisation, market formation, and resource

mobilisation (Bergek et al., 2008; Binz et al., 2014; Hekkert et al., 2007). Our approach for distinguishing between exogenous and endogenous windows of opportunity is meaningful, as the extant literature has treated windows of opportunity as exogenous to the actors in latecomer countries (Yap and Truffer, 2019).

Given these issues, this study posits that the combination of changes in a forerunner's industry legitimacy and a latecomer's efforts to endogenise windows of opportunity drives the latecomer's catch-up. Accordingly, our framework first argues that the changes in forerunners' industry legitimacy create exogenous windows of opportunity (Perez and Soete, 1988) for latecomers by drawing on catch-up theory (Lee and Lim, 2001; Lee and Malerba, 2017) and legitimacy theory (Suchman, 1995). Second, it theorises how latecomers endogenise windows of opportunity for catching up in CoPS by referring to the six core functions of TIS (Carlsson and Stankiewicz, 1991; Yap and Truffer, 2019). Our theoretical assertions are examined by combining longitudinal quantitative data and qualitative accounts derived from archival search and interviews to analyse the catch-up in (South) Korea's nuclear power industry. We focus on Korea, as it is the only latecomer in the global nuclear power industry to achieve the status of a global exporter and is the sixth country to export its technology (after the US, Russia, Canada, France, and Japan) (Hindmarsh and Priestley, 2015).

This study makes some important contributions. First, it enhances

* Corresponding author.

E-mail address: h.yoon@leeds.ac.uk (H.D. Yoon).

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our understanding of the emergence of exogenous windows of opportunity by investigating the legitimacy dynamics in a CoPS industry from a transnational perspective (Binz and Truffer, 2017). Second, combining insights from catch-up theory (Lee and Malerba, 2017) and the TIS framework (Bergek et al., 2008; Binz et al., 2016; Hekkert et al., 2007; Yap and Truffer, 2019), we contribute to prior research by distinguishing between exogenous and endogenous windows of opportunity to explain the determinants of latecomers' catch-up in a CoPS. Collectively, these contributions enable us to develop a deeper understanding of the trajectories from a latecomer's inception to the stage (see Miao et al., 2018, p. 665) when the latecomer becomes an indigenous developer that can export a turnkey CoPS.

The remainder of this study is organised as follows. Section 2 begins with the theoretical background by reviewing the streams of literature on CoPS and latecomers' catch-up. Subsequently, a theoretical framework is proposed in Section 3, which is used to analyse the case. Section 4 explains the research context, analytical approach, data, and methods used in the analysis. Section 5 conducts a longitudinal analysis of South Korea's nuclear power industry. Section 6 discusses our theoretical contributions as well as relevant policy and managerial implications.

2. Latecomer's CoPS and windows of opportunity

Latecomer or less-developed countries acknowledge the importance of CoPS and try to enter into an industry, because it enables their modern industrial and economic progress through technological accumulation and spillover of CoPS across various industries (Hobday et al., 2005). Recent studies on latecomers' CoPS in telecommunication systems (Park, 2012), aircraft (Naghizadeh et al., 2017; Vértesy, 2017), and electricity generation systems (Kiamehr et al., 2013; Safdari Ranjbar, Park, Ghazinoori, and Manteghi, 2019) mainly address how latecomers develop technological capabilities to catch up with market leaders. Park (2012) and Naghizadeh et al. (2017) highlighted the capabilities related to networking, integrative knowledge and skills, and policy-making. Kiamehr et al. (2013) suggested the strategic, functional, and project system integration capabilities needed. These capabilities focused on the importance of mobilising various resources and technologies for system integrators (Davies and Brady, 2000; Davies and Hobday, 2005).

In addition, prior studies on a latecomer's CoPS commonly emphasise that government initiative is essential in the absence of private actors that can take on projects that are as capital and technology intensive as CoPS (Vértesy, 2017; Lee and Ki, 2017; Kiamehr et al., 2015). They show that CoPS industries are primarily led by governments in a top-down manner (Lee and Lim, 2001; Lee and Yoon, 2015; Miao et al., 2018; Park, 2012). Given that many studies on catch-up focus on the rapid process in East Asian countries during a period of dictatorship (e.g. South Korea) or under a communist regime (e.g. China), government leadership is often highlighted in explaining their industry formation and catch-up (Hahm and Plein, 1995; Kim, 2004; Motohashi and Yun, 2007). Although these studies advanced our understanding of key actors' (e.g. government, system integrators) endogenous decisions to mobilise resources and enhance capabilities, they have weak grounding in the literature on windows of opportunity that address both endogenous efforts and exogenous conditions behind latecomer's catch-up (Miao et al., 2018; Safdari Ranjbar, Park, and Kiamehr, 2018).

The concept of 'windows of opportunity' was first used by Perez and Soete (1988) to refer to the role of new techno-economic paradigms in leapfrogging by latecomers. Lee and Malerba (2017) expanded the notion of windows of opportunity by linking them to the building blocks of a sectoral system, thereby proposing three types of windows: technology, demand, and institutional. First, the technology window offers latecomers an opportunity to access and absorb new knowledge and technology that is driven by a shift in the technology paradigm

(Lee and Malerba, 2017; Yap and Truffer, 2019; Vértesy, 2017). Second, the demand window refers to an opportunity provided by substantial changes in demand conditions, such as the creation of new demand, the rapid growth of domestic demand, and abrupt changes in business cycles (Lee and Ki, 2017; Lee and Malerba, 2017; Mu and Lee, 2005). Third, the institutional window is created through government intervention in an industry or through systematic changes in institutional conditions (Lee and Malerba, 2017; Vértesy, 2017).

Despite the significant contributions made by studies on windows of opportunity, prior research shows the need to pay closer attention to at least two issues so as to better understand latecomers' catch-up in CoPS. First, Lee and Malerba (2017, p. 345) explicitly emphasised that 'although business cycles and/or abrupt changes in market have long been the subject of research in economics, their link with strategic choices made by firms, particularly latecomers, has not been explored sufficiently' (e.g. industrial crisis which releases incumbents' resources to latecomers; see Lee and Mathews, 2012). Thus, we argue that disruptive changes in a forerunner's industry legitimacy causing industrial crisis have implications for latecomers' catch-up in a CoPS industry, as it triggers the creation of exogenous windows of opportunity.

Second, although Lee and Malerba (2017, p. 345) explained that 'windows can be exogenous or endogenous, depending upon responses by the various actors of a sectoral system', the extant literature has treated windows of opportunity as exogenous to the actors in latecomer countries (see Yap and Truffer, 2019, p. 1032). Moreover, as a number of catch-up studies tend to focus on technology or capability development strategies (See Yap and Truffer, 2019 p. 1033), little research explicitly analyses how latecomers can form industries by managing a broad set of activities to develop socio-technical systems such as CoPS (Safdari Ranjbar et al., 2018). Hence, we distinguish between exogenous and endogenous windows of opportunity in proposing a research framework. The endogenous windows of opportunity consider key activities in TIS that enable latecomers' successful industry formation (Bergek et al., 2008; Hekkert et al., 2007; Yap and Truffer, 2019). The overarching reasoning in our framework addressing these two issues is articulated in the following section.

3. Theoretical development

Our research framework (see Fig. 1) consists of three building blocks: (1) changes in a forerunner's industry legitimacy associated with exogenous windows of opportunity; (2) endogenous windows of opportunity for a latecomer's industry formation; and (3) a latecomer's catch-up. The main backbone of our building blocks (1) and (2) draws on the work by Lee and Malerba (2017), as they explain that 'windows of opportunity can be exogenous or endogenous' (p. 345). The framework demonstrates a feedback relationship between building blocks (1) and (2). On the one hand, the arrow from building block (1) to (2) describes a latecomer's passive response to exogenous windows of opportunity derived from the changes in forerunners' industry legitimacy. In fact, in the early stage of catch-up, most latecomers passively respond to the exogenous windows by simply importing technologies from forerunners (Hobday, 1995). On the other hand, the arrow from building block (2) to (1) represents a latecomer's active response to the changes in a forerunner's industry legitimacy. As a latecomer's industry grows, it can actively exploit exogenous windows of opportunities with its effective TIS.

In building block (1), we explain the role of a forerunner's industry legitimacy, which is defined in our study as the perceived consonance of an industry with its institutional environment, i.e. a socially constructed set of norms, values, beliefs, and practices in its context (Scott, 2001; Suchman, 1995). Grounded in the work of Suchman (1995) and Binz et al. (2016), we posit that industry legitimacy can be divided into three key dimensions. Pragmatic legitimacy is the most basic form of legitimacy, as it rests on self-interest from the perspective of the value delivery of an industry to the most immediate

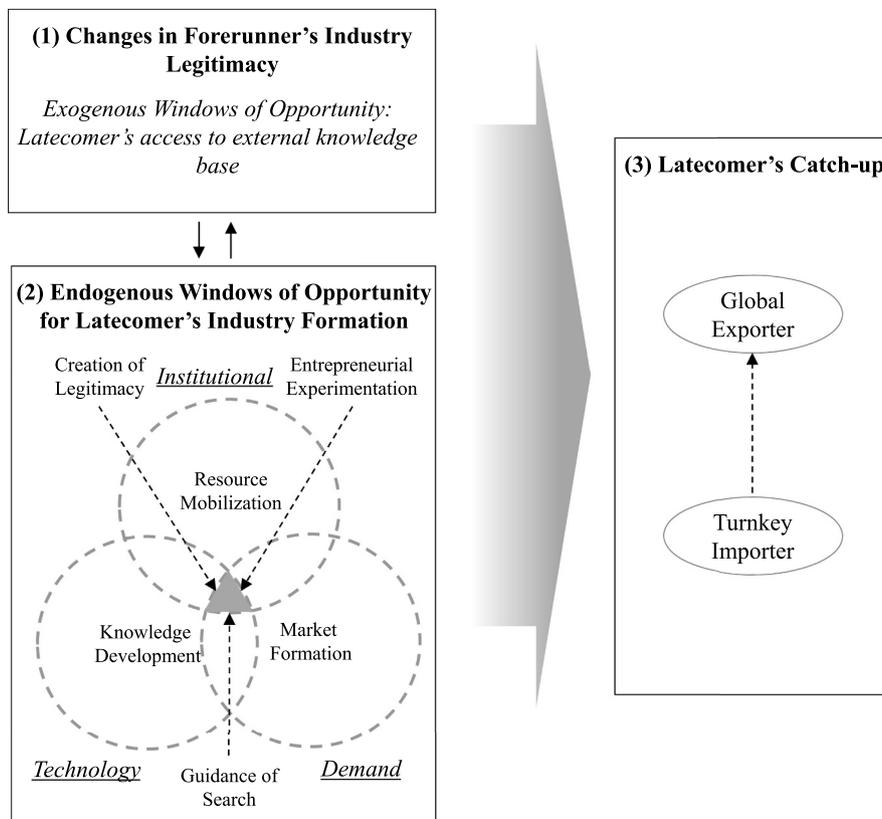


Fig. 1. Research framework.

audiences (Binz et al., 2016). Moral legitimacy is normative, which is based on an evaluation that industrial activities are consistent with existing regulations and moral obligations (Binz et al., 2016). The final kind of legitimacy, cognitive legitimacy, is the degree to which an industry is seen as taken for granted (Binz et al., 2016).

Subsequently, we argue that the loss of industry legitimacy by forerunners is a relevant issue in a CoPS industry that deserves attention because it induces a downturn in forerunners' industry, thereby releasing their resources to latecomers (Jonsson et al., 2009; Lee and Mathews, 2012; Mathews, 2005). Forerunners are deemed as lacking legitimacy when their activities are not desirable or do not conform to prevailing societal norms and standards (Hiatt et al., 2009; Kim et al., 2016). Insufficient industry legitimacy may lead to unstable links with users, distract their attention, and the withholding of material or ideational support to an industry (Aldrich and Fiol, 1994). As a result, forerunners experiencing industrial crisis derived from insufficient industry legitimacy look for new business opportunities outside their domestic market (e.g. building a new CoPS in latecomer countries). In particular, given the low bargaining power of the forerunner derived from its industrial crisis, technology transfer terms can easily be included in business arrangements between a forerunner and a latecomer. In other words, a loss of a forerunner's industry legitimacy can induce discounts on state-of-the art technologies for latecomers to easily acquire and accumulate forerunner's core knowledge base and technologies. Therefore, it can serve as an exogenous window of opportunity for latecomers.

In addition to the change in a forerunner's industry legitimacy, providing favourable exogenous windows of opportunity for latecomer's catch-up, building block (2) explains that latecomers need to manage a set of innovation activities to endogenise windows of opportunity (Yap and Truffer, 2019) that occur in the domestic context of the latecomer country. Specifically, we draw on the six TIS core activities (Bergek et al., 2008; Binz et al., 2014; Hekkert et al., 2007) by considering the three perspectives on windows of opportunity (see

building block (2) in Fig. 1).

First, the technological perspective covers activities that help latecomers overcome their intrinsic weakness in technological capability. The activities include knowledge development, the creation of legitimacy, guidance of search, and entrepreneurial experimentation. Given the technological complexity of a CoPS, which requires integration of diverse inter-dependant components and sub-systems, knowledge development is critical during the industry inception and serves as a foundation for catch-up (Lee and Yoon, 2015; Park, 2012). The creation of legitimacy through institutional alignment in the domestic context can also facilitate a variety of technology development activities (Bergek et al., 2008; Hekkert et al., 2007). Guidance of search can promote knowledge accumulation in a specific technological field corresponding to the emergence of public expectations, visions, and beliefs in the growth of an industry (Bergek et al., 2008; Park, 2012; Yap and Truffer, 2019). Entrepreneurial experimentation to combine technological knowledge with market applications can contribute to a latecomer's technological accumulation (Hekkert et al., 2007; Tigabu et al., 2015).

Second, the demand perspective addresses the activities that drive growth in the domestic market, including market formation, guidance of search, entrepreneurial experimentation, and the creation of legitimacy. Market formation in latecomers' CoPS is generally initiated by governments in the form implementing a variety of policy instruments including tax subsidies, support of new standards, and public procurement (Park, 2012; Vértésy, 2017). Guidance of search driven by the changing preferences of society and lead customers can create demand for a new technology (Bergek et al., 2008; Hekkert et al., 2007). Similarly, we expect that entrepreneurial experimentation creates new solutions to existing problems, thereby creating new market demand (Hekkert et al., 2007). Legitimacy creation takes place through the development of informal industrial alliances (e.g. amongst supportive advocacy coalitions, interest groups, networks, intermediaries) that contribute to the creation of early (niche) markets which act as

beachheads for the mainstream market (Bergek et al., 2008; Binz et al., 2014; Hekkert et al., 2007).

Third, the institutional perspective encompasses the activities led by both government authorities (Lee and Malerba, 2017) and civil society (Binz and Truffer, 2017; Wirth et al., 2013) that include resource mobilisation, the creation of legitimacy, the guidance of search, and entrepreneurial experimentation. Mobilising resources (e.g. finance, human capital) based on favourable government regulation and a supportive culture in the industry is critical for industry formation and catch-up (Park, 2012; Vértesy, 2017; Wirth et al., 2013). Various institutional instruments (e.g. maintenance of favourable intellectual property regimes, provision of subsidies, and the construction of a shared belief system) can be a catalyst for the creation of industry legitimacy (Hekkert et al., 2007; Wirth et al., 2013). Guidance of search as a technology selection process comes in the form of government policy and corresponding regulations (Bergek et al., 2008; Hekkert et al., 2007). Entrepreneurial experimentation is also important for a latecomer's industry formation through political lobbying to obtain specific policies or regulations that support favourable development of an industry (Hekkert et al., 2007; Jacobsson and Bergek, 2011).

As a whole, the framework explains that the combination of (1) changes in a forerunner's industry legitimacy (creating windows of opportunity for a latecomer to gain access to an external knowledge base) and (2) endogenous windows of opportunity (triggering the latecomer to become committed to technological innovation activities) contributes to latecomers' successful catch-up. The final output of the framework, 'catch-up', is evidenced from its evolution from a turnkey importer, in which latecomers rely on subcontracting arrangements to accumulate production and manufacturing knowledge (i.e. status of original equipment manufacturer [OEM]) (Hobday, 1995) to a global exporter, in which latecomers export their indigenously developed CoPS on the global market (i.e. similar to the status of original brand manufacturer [OBM]) (Kiamehr et al., 2015; Lee and Yoon, 2015; Vértesy, 2017).

4. Research design

4.1. Context

Nuclear power plants (NPP) and their related systems are considered typical CoPS (see Davies and Brady, 1998; Dedehayir et al., 2014; Hobday, 1998; Markard and Truffer, 2006; Son and Choung, 2014; Walker, 2000). This is because the plants consist of complex and technology-intensive sub-systems, such as a nuclear steam supply system (NSSS), turbine generator system, and other supporting and auxiliary systems. They are structured in a hierarchical manner in which the sub-systems are also composed of many parts and a lot of equipment. In this structure, each sub-system, part, and piece of equipment is highly independent and interrelated and should be integrated to ensure the optimal performance of the NPPs. Moreover, because of its high cost, customised delivery, and low-volume production, regulatory institutions intervene in the market in terms of local market creation, safety management, local supply chain protection, and financing.

In addition to the representativeness of NPPs, the industry is ideal for investigating the role of legitimacy in creating exogenous windows of opportunity because it has experienced many ups and downs as a result of the changes in societal values and the dissenting views between technology proponents and anti-nuclear activists (Garud et al., 2010; Geels and Verhees, 2011; Ross and Staw, 1993). The nuclear power industry's biggest challenge is 'not one of technical or even cost difficulties, but of maintaining a veneer of legitimacy' (Stoett, 2003, p. 99). After the Fukushima nuclear accident in 2011, the legitimacy of nuclear power industry severely declined worldwide (Froggatt and Schneider, 2011; Kim et al., 2013; Ramana, 2011).¹ This event shows

that legitimacy of nuclear power industry can be withdrawn by accidents or industrial hazards or when a focal actor's activities are undesirable or do not conform to prevailing societal norms (Hiatt et al., 2009; Kim et al., 2016).

Despite the disruptive consequences of these hazardous events, nuclear power is still recognised as an attractive energy source. Many studies have highlighted the contribution of nuclear power in reducing CO₂ emissions (e.g., Apergis et al., 2010; IEA, 2018; Menyah and Wold-Rufael, 2010). Moreover, it was found that nuclear power has a higher utilisation rate (ratio of its actual output over a period of time to its potential output at full capacity) than photovoltaic (i.e. solar) and wind power (Zhang et al., 2012). Because of these environmental and economic benefits, many governments are re-considering the share of nuclear power in their future energy generation (Cîrstea et al., 2018; IEA, 2018; Oshiro et al., 2017). In fact, even though China suspended the approval of new NPPs since the Fukushima nuclear accident in 2011, it officially resumed approving new coastal nuclear power projects in December 2014 (Guo and Guo, 2016; World Nuclear Association, 2019). These accounts show that catching up in the nuclear power industry is neither on the wrong track in industrial development nor driven by a forerunner's entry into alternative industries (e.g. renewable energy).

4.2. Analytical approach

Our analysis investigates the process of technological advancement in the Korean nuclear power industry based on critical changes in the legitimacy of the global nuclear power industry, opening of exogenous windows of opportunity, and indigenous efforts to endogenise windows of opportunity for catch-up. In particular, regarding the operationalisation of legitimacy, we focus on industry legitimacy (Markard et al., 2016) as we are mainly interested in capturing how knowledge or technology is liberated and transferred from forerunner to latecomer corresponding to the change in the forerunner's industry legitimacy. We rely on the three types of legitimacy (i.e., pragmatic, moral, and cognitive) in Suchman (1995) in our analysis. Whereas prior studies on industry legitimacy tend to treat legitimacy at the aggregate level, our analysis explains the dynamics of transnational industry legitimacy using a variety of dimensions (Binz et al., 2016). This is mainly because various characteristics embedded in CoPS (e.g. NPP safety, mitigation of CO₂ emissions by NPPs, economic efficiency of nuclear energy, technological and economic spillover to downstream industries) naturally have different implications for legitimacy.

Subsequently, we use a multi-dimensional approach to capture pragmatic, moral, and cognitive legitimacy. First, pragmatic legitimacy is identified by considering the supply of low-cost electricity, economic growth, and enhanced profitability stemming from the formation of the nuclear power industry and technological self-reliance. Second, moral legitimacy is traced through key social movements that address issues on 'civilian nuclear power' (Gamson and Modigliani, 1989), eco-friendliness in power generation, and anti-nuclear initiatives (Beelitz and Merkl-Davis, 2012; Geels and Verhees, 2011; Walker and Wellock, 2010). Lastly, cognitive legitimacy is addressed by investigating whether the nuclear power industry is perceived as an essential part of national security and an inevitable energy source and has

¹ In September 2012, the Japanese government announced an 'innovative energy-environmental policy' aimed at achieving zero nuclear power generation in the 2030s (Homma and Akimoto, 2013). Germany shut down all seventeen of its operational nuclear power reactors, and Switzerland agreed to phase out its five aging power reactors (Froggatt and Schneider, 2011). Italy decided to exclude nuclear energy from its future energy mix (Froggatt and Schneider, 2011). Furthermore, U.S. public support for building new reactors declined from 57 percent in 2008 to 43 percent in March 2011 (Ramana, 2011). More than forty countries have redirected their policies in nuclear energy after a change in public attitudes after the accident (Kim et al., 2013).

safeguards to protect people in the event of industrial disasters (e.g. Three Mile Island, Chernobyl) (Renn, 1990; Geels and Verhees, 2011; Jasanoff and Kim, 2009). These dimensions of legitimacy can expand or contract, depending on the fulfilment of value for constituents and conformance with the institutions, societal norms, and beliefs at a given moment (Bitektine, 2011; Geels and Verhees, 2011; Jasanoff and Kim, 2009; Renn, 1990).

4.3. Data and method

We adopted a longitudinal investigation method along with detailed narratives to analyse the catch-up in the Korean nuclear power industry (Eisenhardt and Graebner, 2007; Yin, 2014). To this end, we use a process-tracking method to identify the details of cause and effect across the three building blocks of our framework (George and Bennett, 2005; Yin, 2014). To track the catch-up, our analysis documents key technological advancement across multiple stages from being an importer to becoming a global exporter.

Our primary data were collected through a series of interviews and e-mail communications with experts in the Korean nuclear power industry. We contacted a principal administrator who has been working for 30 years for the largest organisation in the Korean nuclear power industry, the Korea Atomic Energy Research Institute (KAERI), and has been the head of the auditing and technological commercialisation department. We also interviewed the former project manager of the first national research and development project for self-reliance in nuclear power and the former director of technical cooperation at the International Atomic Energy Agency (IAEA). Moreover, to ensure the objectivity of our analysis, we collected additional primary data from a number of innovation scholars who have investigated the Korean nuclear power industry. In total, we conducted 12 interviews with five experts in the Korean nuclear power industry (8/2017, 5/2018, 7/2018), including several pilot interviews in a pre-study phase (1/2017–2/2017), and the other main interviews with experts in innovation management studies to ensure the objectivity of our analysis (2/2017, 7/2018, and 9/2018).

The interview questions were distributed in advance by e-mail to allow efficient and accurate communications (Miles and Huberman, 1994). Each interview lasted approximately one or two hours, and the interviews were transcribed within 24 h to enhance the reliability of the interviews. We also shared the draft of our study with the interviewees to receive their feedback. This means that the interviews serve as an important source of historical accounts based on their extensive knowledge and experience in the Korean nuclear power industry. The combination of interviews with a variety of experts, such as public administrators, research scientists, and innovation scholars, helped in the triangulation of our findings (Eisenhardt, 1989; Yin, 2014).

In a triangulation effort, we collected a wide range of secondary data—i.e., academic journal articles, press articles, research papers, and archival records. To clarify the scope of our secondary data collection, we first listed the major firms, research institutes, and other stakeholders in the Korean nuclear power industry. By discussing our extensive list with the interviewees, we were able to identify key actors, such as KAERI, the Korea Electric Power Corporation (KEPCO), KEPCO Engineering & Construction (KEPCO E&C), Doosan Heavy Industries & Construction (Doosan), and relevant ministries, including their agencies involved in the formation of Korea's nuclear power industry, as shown in Fig. 2. Also, we identified the important foreign entities comprising an external knowledge base corresponding to the change in a forerunner's legitimacy based on our secondary data collection (see Fig. 2). Lastly, we collected additional secondary statistics from the IAEA, KAERI, KEPCO (including its subsidiaries), and Statistics Korea (see Table 1).

5. Results

Our analysis consists of three periods (see Fig. 3): (1) from 'turnkey' to 'non-turnkey' importer (late 1960s–early 1980s), (2) from 'non-turnkey' importer to technological self-reliance (late 1980s–late 2000s), and (3) from technological self-reliance to the global exporter (2010–). Table 2 provides details on the catch-up progress in the Korean nuclear power industry considering the localisation rate, the role of key actors in formation of the industry, and the level of technological capability.

5.1. From 'Turnkey' to 'Non-Turnkey' imports from the late 1960s to the early 1980s

Korea obtained its opportunity to access nuclear technology through the support of the U.S. in 1950s. The other great power, the Soviet Union, succeeded in developing a nuclear weapon later than the U.S., during the cold war era in the early 1950s. As a result, the U.S. did not maintain its monopoly on the development of nuclear technology. The U.S. recognised the importance of spreading its technology to combat the proliferation of nuclear weapons (KAERI, 2007) and in December 1953 announced 'Atoms for Peace' to promote the application of nuclear technology for peaceful purposes (Chernus, 2002; Weart, 1988). This initiative enhanced the moral and cognitive legitimacy of nuclear technology amongst pro-U.S. countries (Balogh, 1991), enabling Korea to attain an opportunity to use the technology by signing a cooperation agreement with the U.S. in 1956 (Choi et al., 2009; Park, 1992). This shows that the increase in the legitimacy of nuclear energy created a technology window for a latecomer to access the forerunner's technology.

Moreover, the increase in the legitimacy of nuclear technology in the eyes of the Korean public that advocated the view of 'Atoms for National Development and Security' supported the nuclear power generation in Korea (Jasanoff and Kim, 2009; Kim and Byrne, 1996). Koreans understood the need for it, because the country's unprecedented economic growth had massively increased the rate of growth in electricity consumption. In addition, they had experienced having their electricity supply cut by North Korea in 1948 because of political tension on the Korean Peninsula (KAERI, 2007). As a result, securing a stable electricity supply was prioritised on the national development and security agenda (Sung and Hong, 1999; Valentine and Sovacool, 2010).

Accordingly, the South Korean government pushed ahead with NPP construction under the Second Five-year Economic Development Plan (1967–1971) (Choi et al., 2009; KAERI, 2007). In June 1968, it decided to build its first NPP, Kori 1 (1972),² which had an electricity-generating capacity of 587 MWe (megawatt electric, or the electric output of a power plant in megawatts), based on a turnkey contract, naming KEPCO as the operator of the NPP (KAERI, 2007; Park, 1992). Westinghouse (WH), with its pressurised water reactor, was selected to act as the nuclear steam supply system (NSSS) supplier, prime contractor, and project manager for the construction of this NPP and designated another foreign firm, Gilbert Associates (GIL), to take charge of architectural engineering. Although the turnkey contract meant that Korea was fully dependant on a foreign firm throughout the process of NPP construction, it deployed its resources to build upon the knowledge developed and provided by forerunners (Choi et al., 2009; Hong, 2016).

Subsequently, during the two oil shocks in the 1970s, Korea expanded its NPP market, which enhanced the cognitive and pragmatic legitimacy of nuclear power-based electricity generation. The oil shocks forced the Korean government to recognise the importance of NPP expansion for its energy security and economic growth (Choi et al., 2009; Kim and Byrne, 1996). Major energy-consuming sectors in Korea

² The number in parentheses after the plant name indicates the year that construction on each plant started.

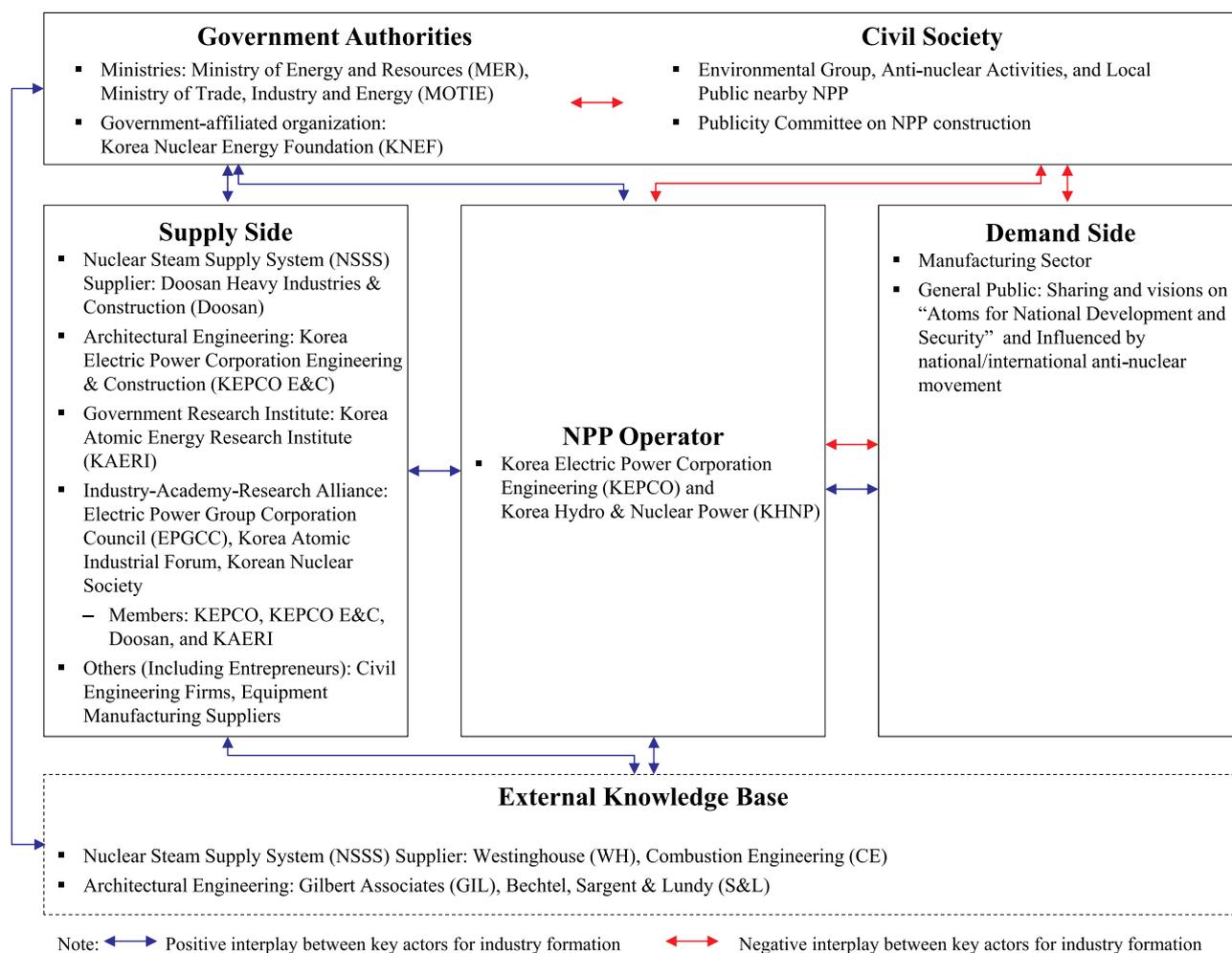


Fig. 2. Key actors in Korean nuclear power industry.

Table 1
Data sources.

Type	Collection period	Major content
Primary data		
Face-to-face and telephone interviews	1/2017–2/2017, 8/2017, 5/2018, 7/2018, 9/2018	Historical narratives of Korea’s technological learning in NPPs; International technology transfer agreements; Validation of the analyses results
Secondary data		
Korea Power Exchange (subsidiary of KEPCO)	6/2018	Historical data on the weight of nuclear power for electricity generation in Korea based on Electric Power Statistics Information System (EPSIS); -Coverage: From 1961 to 2015
Statistics Korea	5/2018	Historical data on electricity generation capacity and electricity usage in Korea; -Coverage: From 1962 to 2016
IAEA	5/2018	Historical data on the number of NPPs under construction and operation by country.-Coverage: From 1960 to 2017; -Coverage: From 1978 to 2017
KAERI	4/2018–5/2018	Technical and industrial reports on Korean and global NPPs: KAERI (2007), ‘Investigation on the 50 Years of Nuclear Development in Korea’. Ministry of Science and Technology Korea

(e.g. steel, petrochemical, and shipbuilding) (Choi et al., 2009) supported the NPP expansion in their self-interest to secure a stable and low-cost electricity supply, out of pragmatism (KAERI, 2007). The Korean public also recognised that nuclear power was an irreplaceable source of energy in their country, which is deficient in natural resources. This favourable public perception confirms the strong presence of cognitive legitimacy, which highlights the importance of being taken for granted. At the same time, NPPs were morally legitimised with a consensus that it could replace coal-fired power generation, which causes air pollution and other environmental problems (Smith, 1986).

The enhanced legitimacy of NPPs in Korea further encouraged the government to form a market, mobilise resources, and develop knowledge. Since the first oil shock in October 1973, the Korean government approved the construction of the six new NPPs (Kori 2 and Wolsong 1 in 1978, Kori 3 and 4 in 1980, and Hanbit 1 and 2 in 1981) (see Table 2), whose total electricity generation capacity was about 5000 MWe (MOTIE and KHNP, 2016). In 1977 the government established the Ministry of Energy and Resources, which was responsible for designing and implementing policy on the nuclear power industry and managing the construction, operation, and maintenance of NPPs

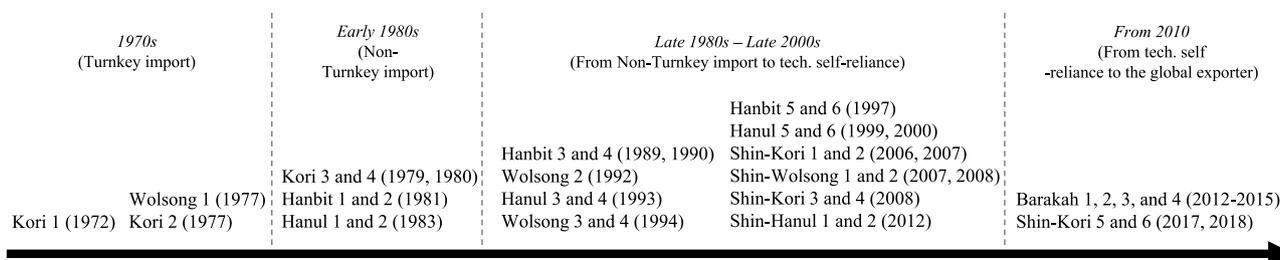


Fig. 3. Construction year of Korean nuclear power plants.

Table 2

Catch-up of the Korean nuclear power industry: From Turnkey Importer to Global Exporter.

Source: Adapted from Ahn and Han (1998), Choi (1980), Choi et al. (2010), Holt (2010), Hong (2016), IAEA (2019), KEEI (2012), KIER (2017), MOST (2007), MOTIE and KHNP (2016), National Archives of Korea (2006a), National Archives of Korea (2006b), Park (1992), Sung and Hong (1999), and authors' analysis based on the interviews.

No. ^a	Name	Capacity (MWe)	Localization Rate ^b	Prime Contractor ^c	Architectural Engineering	Project Manager	Status of Tech. Capability (Brand Name)	Construction Start Date	Commercial Operation Date	Current Status
1	Kori 1	587	8%	WH	GIL	WH	Turnkey Import	Apr. 1972	Apr. 1978	Shut Down
2	Wolsong 1	679	14%	AECL	AECL	AECL	Turnkey Import	Oct. 1977	Apr. 1983	Shut Down
3	Kori 2	650	13%	WH	GIL	WH	Turnkey Import	Dec. 1977	Jul. 1983	Operating
4	Kori 3 ^d	950	29%	WH	Bechtel	KEPCO	Non-Turnkey Import	Oct. 1979	Sep. 1985	Operating
5	Kori 4 ^d	950						Apr. 1980	Apr. 1986	
6	Hanbit 1	950	35%	WH	Bechtel/	KEPCO	Non-Turnkey Import	Jun. 1981	Aug. 1986	Operating
7	Hanbit 2	950			KEPCO E&C			Dec. 1981	Jun. 1987	
8	Hanul 1	950	40%	FRAM	FRAM, ALS/	KEPCO	Non-Turnkey Import	Jan. 1983	Sep. 1988	Operating
9	Hanul 2	950			KEPCO E&C			Jul. 1983	Sep. 1989	
10	Hanbit 3 ^e	1000	74%	Doosan,	KEPCO E&C/S&L	KEPCO	Licensed from	Dec. 1989	Mar. 1995	Operating
11	Hanbit 4 ^e	1000		KAERI/CE			CE (System80) ^f	May. 1990	Jan. 1996	
12	Wolsong 2	700	58%	AECL/DHI	AECL/	KEPCO	Non-Turnkey Import	Jun. 1992	Jul. 1997	Operating
					KEPCO E&C					
13	Hanul 3	1000	75%	Doosan,	KEPCO	KEPCO	Self-Reliance	Jul. 1993	Aug. 1998	Operating
14	Hanul 4	1000		KAERI/CE	E&C		(KSNP)	Nov. 1993	Dec. 1999	
15	Wolsong 3	700	67%	AECL/DHI	AECL/	KEPCO	Licensed from AECL	Mar. 1994	Jul. 1998	Operating
16	Wolsong 4	700			KEPCO E&C		(CANDU-600)	Jul. 1994	Oct. 1999	
17	Hanbit 5	1000	79%	Doosan, KEP	KEPCO	KHNP	Self-Reliance	Jun. 1997	May. 2002	Operating
18	Hanbit 6	1000		CO E&C/CE	E&C		(OPR1000(KSNP +))	Nov. 1997	Dec. 2002	
19	Hanul 5	1000	79%	Doosan, KEP	KEPCO	KHNP	Self-Reliance	Oct. 1999	Jul. 2004	Operating
20	Hanul 6	1000		CO E&C/CE	E&C		(OPR1000(KSNP +))	Sep. 2000	Apr. 2005	
21	Shin-Kori 1	1000	78%	Doosan, KEP	KEPCO	KHNP	Self-Reliance	Jun. 2006	Feb. 2011	Operating
22	Shin-Kori 2	1000		CO E&C/CE	E&C		(Improved OPR1000)	Jun. 2007	Jul. 2012	
23	Shin-Wolsong 1	1000		Doosan, KEP	KEPCO	KHNP	Self-Reliance	Nov. 2007	Jul. 2012	Operating
24	Shin-Wolsong 2	1000		CO E&C/CE	E&C		(Improved OPR1000)	Sep. 2008	Jul. 2015	
25	Shin-Kori 3 ^g	1400	95% ^h	Doosan, KEPCO E&C	KEPCO E&C	KHNP	Self-Reliance (APR-1400)	Oct. 2008	Dec. 2016	Operating
26	Shin-Kori 4	1400						Aug. 2009	Aug. 2019	
27	Shin-Hanul 1	1400	100% ⁱ	Doosan, KEPCO E&C	KEPCO E&C	KHNP	Self-Reliance (APR-1400)	Jul. 2012		Under Construction
28	Shin-Hanul 2	1400						Jun. 2013		
29	Barakah 1	1400	95% ⁱ	Doosan, KEPCO E&C	KEPCO E&C	KEPCO/ KHNP	Global Exporter (APR-1400)	Jul. 2012		Under Construction
30	Barakah 2	1400						Apr. 2013		
31	Barakah 3	1400						Sep. 2014		
32	Barakah 4	1400						Jul. 2015		
33	Shin-Kori 5	1400	100%	Doosan, KEPCO E&C	KEPCO E&C	KHNP	Self-Reliance (APR-1400)	Apr. 2017		Under Construction
34	Shin-Kori 6	1400						Sep. 2018		

^a Listed in the order of construction start (commercial operation).

^b Represents the rate of domestic supply by considering the financial value of components.

^c Prime Contractors are NSSS suppliers.

^d Used as the reference model for 2 successive NPPs (Hanbit 1 and 2).

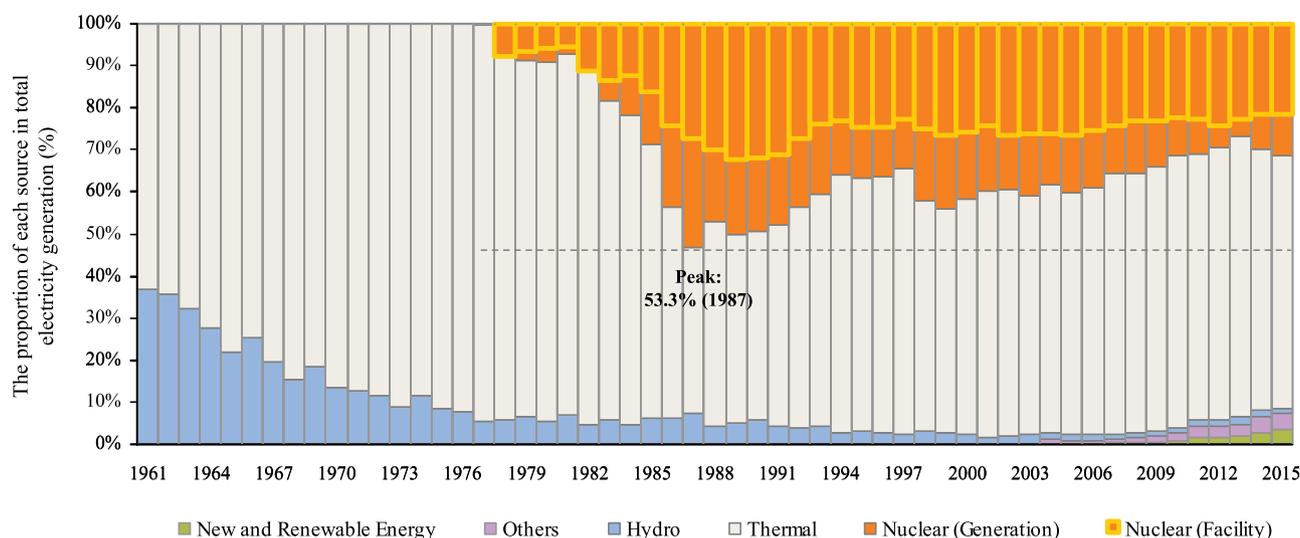
^e Used as the reference model for 10 successive NPPs (Hanul 3 and 4, Hanbit 5 and 6, Hanul 5, and 6, Shin-Kori 1 and 2, Shin-Wolsong 1 and 2).

^f Scaled-down version of the System 80 of CE with 1300 Mwe.

^g Used as the reference model for Barakah 1-4 NPPs.

^h Achieved localization except the MMIS (Man Machine Interface System) and RCP (Reactor Coolant Pump).

ⁱ Based on the localization and application of MMIS and RCP.



Source: Authors' analysis based on Electric Power Statistics Information System (EPSIS) of Korea

Note: Excluded the electricity generation capacity from self-generation segment

Fig. 4. Nuclear power for electricity generation in Korea.

(Hong, 2016). The ministry adhered in particular to 'economic load despatch approaches'³ and prioritised nuclear power in Korea's energy mix. As a result, in 1987, when seven NPPs were in commercial operation, the proportion of nuclear power in electricity generation reached a peak of 53.3% (see Fig. 4).

At the peak, many local entrepreneurial firms in civil and construction engineering, equipment manufacturing, and architectural engineering sectors entered the industry in response to the formation of a domestic NPP market. Specifically, to encourage the knowledge development related to architectural engineering, the Korea Atomic Energy Research Institute (KAERI), KEPCO, and eleven private firms co-established Korea Nuclear Engineering (afterwards, KEPCO E&C as a subsidiary of KEPCO) in 1976 with the goal of training engineers and offering technical consultation (Hong, 2016; KAERI, 2007). Furthermore, an industrial alliance (e.g. Korean Atomic Industry Forum [1972]) and academic societies (e.g. Korean Nuclear Society [1968]) were established with government approval for knowledge development and the creation of legitimacy, to enhance public acceptance of nuclear power.

In particular, in the late 1970s, to facilitate the development of local knowledge based on the absorption of foreign technology, the Korean government initiated six NPP construction projects, from Kori 3 to Hanul 2 (see Table 2) under non-turnkey contracts (Choi et al., 2009; Jasanoff and Kim, 2009; Sung and Hong, 1999). Specifically, the Korean government constructed two NPPs in the same place with the same electricity capacity and reactor type. The government expected this approach to have an advantage in enhancing project management capability and in developing a local supply chain under non-turnkey contracts based on economies of scale. This approach was also applied in the construction of Kori 3 and 4, Hanbit 1 and 2, and Hanul 1 and 2. The fourth and fifth NPPs (Kori 3 and 4) are reference models for two successive NPPs (Hanbit 1 and 2) with regard to their architectural engineering, equipment manufacturing, and civil engineering.

The creation of the market under non-turnkey contracts promoted knowledge development for some key actors in the Korean nuclear power industry. Specifically, KEPCO was designated as the project manager in charge of civil engineering in the construction of Kori 3 and

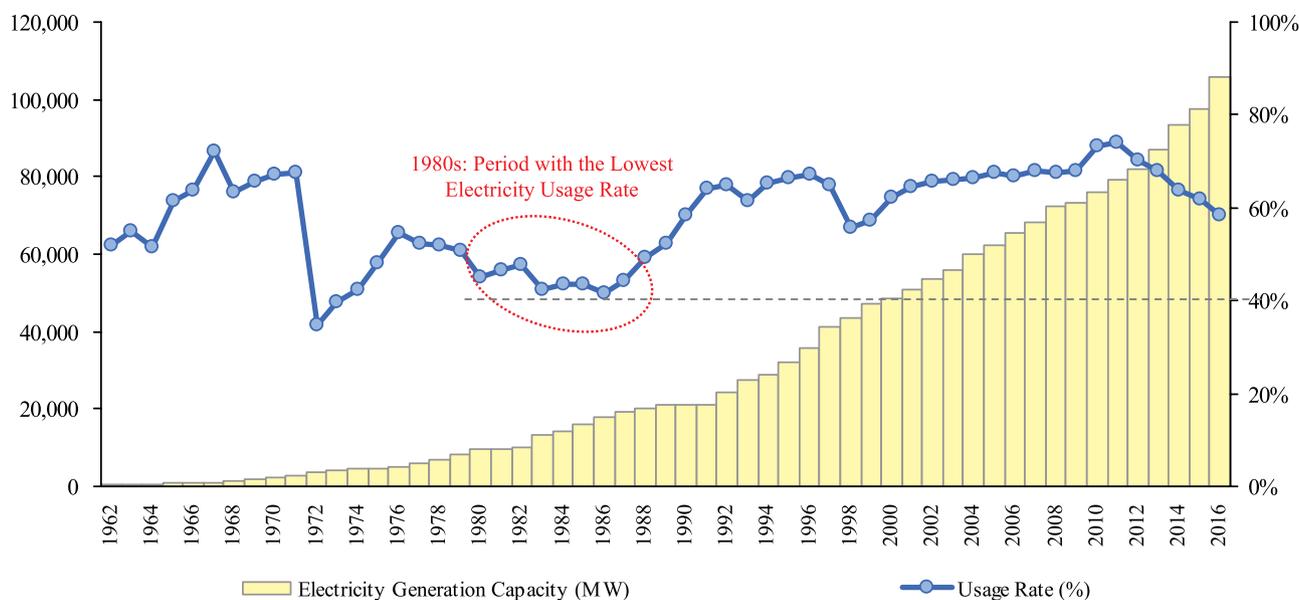
4 (Holt, 2010). In addition, KEPCO specified the target localisation rate and explicitly demanded that foreign partners license technologies related to equipment manufacturing and architectural engineering (Choi et al., 2009; Jasanoff and Kim, 2009; KAERI, 2007). This encouraged the participation of local entrepreneurial firms in the construction of NPPs as sub-contractors to assimilate and internalise advanced technology (Choi et al., 2009; Park, 1992; Sung and Hong, 1999). As a result, the localisation rate in the engineering, equipment procurement, and construction gradually increased from 8 to 14% in the first three turnkey contract-based NPPs to 29–40% in the successive six non-turnkey contract-based NPPs (from Kori 3 to Hanul 2) (see Table 2). KEPCO E&C acted as a sub-contractor in the architectural engineering of Hanbit 1 and 2 and Hanul 1 and 2 and successfully acquired design capabilities (Sung and Hong, 1999).

5.2. From 'Non-Turnkey' imports to technological self-reliance from the late 1980s to the late 2000s

Despite Korea's transition from turnkey to non-turnkey importer, the dependence on foreign contractors for architectural engineering restricted knowledge development by local firms. Because of this technological dependence, KEPCO encountered a sharp increase in NPP construction costs (Hanbit 1 and 2), even though Kori 3 and 4 used the same contractor, Bechtel (MOST, 2007) due to insufficient knowledge of NSSS design, architectural engineering, and technical and economic feasibility analysis. A multiple sourcing strategy based on guidance of search led by the Korean government in selecting prime contractors (WH, AECL, and FRAM) for their first nine NPPs (see Table 2) hindered Korean firms from effectively accumulating and integrating various knowledge and skills.

After encountering this problem, major actors in the industry (i.e. KEPCO, KEPCO E&C, Doosan, and KAERI) recognised the value of technological self-reliance. From a pragmatic perspective, to further reduce the construction cost, they organised the Electric Power Group Corporation Council (EPGCC) supervised by the Ministry of Energy and Resources in April 1985. They suggested 'standardisation' of NPPs, which implies repetitive design and the construction of pressurised water reactor-type NPPs to accumulate technological capability via 'learning by repetition' (Ahn and Han, 1998; Hong, 2016). For standardisation, EPGCC recommended compulsory technology transfer from forerunners with the contract on Hanbit 3 and 4 (Ahn and

³ The approach prefers an electricity source for baseload operation, which satisfies electricity demand at the lowest possible cost compared with alternatives, such as oil, natural gas, and renewable energy



Source: Authors' analysis based on Korean Statistical Information Service database provided by Statistics Korea
 Note: Excluded the electricity generation capacity from self-generation segment

Fig. 5. Electricity generation capacity and electricity usage in Korea (MW,%).

Han, 1998). Although the compulsory technology transfer was very costly, the EPGCC believed that it was crucial to achieve technological self-reliance (Sung and Hong, 1999). Following the suggestion of the council, the Korean government invited bids with the condition of compulsory technology transfer on NSSS design in October 1985 (Hong, 2016; KAERI, 2007).

In particular, the KAERI played a critical role in achieving self-reliance to reduce the construction cost and maintain the pragmatic legitimacy of the industry with its active engagement and resource commitment. At the time, the political dispute between the U.S. and Korean governments caused by suspicion of nuclear weapons development could have resulted in the closure of the KAERI (Jasanoff and Kim, 2009). Furthermore, the fact that the electricity use rate had reached the lowest point in its history, around 40% during the 1980s (Fig. 5) because of economic recession, threatened the KAERI's existence. Despite the unfavourable circumstances, the KAERI worked hard to achieve technological self-reliance and maintain the pragmatic legitimacy of the industry. Coincidentally, public perception about the legitimacy of nuclear power industry at the time remained impregnable, thereby supporting the self-reliance effort (Jasanoff and Kim, 2009).

Beyond the increase in nuclear power industry legitimacy in the domestic market, the severe decrease in the cognitive legitimacy of the nuclear power industry in transnational contexts was triggered by critical accidents at Three Mile Island in the U.S. in March 1979 and Chernobyl in the Soviet Union in April 1986. The aftermath of these incidents created windows for Korea to pursue technological self-reliance, because the pause in the legitimacy of nuclear power halted construction of or cancelled orders for NPPs around the world (Choi et al., 2009; Sung and Hong, 1999). The U.S. had not constructed any new NPPs for 35 years (Davies, 2012). Most of the NSSS suppliers in the world, i.e., WH, FRAM, AECL, CE (Combustion Engineering), and General Electric, experienced serious financial problems. For instance, Babcock & Wilcox, the NSSS suppliers of the Three Mile Island NPP, went bankrupt. Additionally, as the economic feasibility of using gas-fired power plants for base load electricity had been confirmed (Islas, 1999; Watson, 1997), the moral legitimacy of NPPs as an eco-friendly energy source was significantly diminished. Thus, the severe decrease in the legitimacy of forerunners' nuclear power industry

empowered latecomers to negotiate compulsory technology transfer on favourable terms.

In sum, forerunners' decreased industry legitimacy provided a window of opportunity for Korea to gain stronger bargaining power in acquiring core technology from forerunners by mobilising resources at a lower cost (Lee and Malerba, 2017; Lee and Mathews, 2012). In other words, Korea was able to take advantage of a significant downturn in global nuclear power industry in order to expand its knowledge and skills and to internalise them in an affordable manner (Lee and Mathews, 2012; Mathews, 2005). The effect of the global industry downturn was even more critical for Korea in acquiring the technology than the increase in the construction cost of Hanbit 3 and 4 by more than 1.5 times higher over that of previous NPPs because of the massive licensing fee.

With this shift in bargaining power, KEPCO and KAERI succeeded in negotiating a compulsory technology transfer (especially NSSS design) contract with CE in April 1978 to construct Hanbit 3 and 4 (Hong, 2016). The contract included the transfer and sharing of technical documents, computerised design codes, and patents. It also specified the provision of job training and consultation by CE to carry out joint design and development projects (Ahn and Han, 1998; Sung and Hong, 1999; Hong, 2016; see Table 4). KEPCO and KAERI had access to all the explicit knowledge and know-how of CE engineers (Sung and Hong, 1999). In particular, the condition of joint design and development specified that all the risks regarding the delay or performance problems are responsible for CE, and all relevant knowledge had been transferred to KEPCO and KAERI within three years of signing of the contract.

KAERI and KEPCO took advantage of the compulsory technology transfer terms, and their role in knowledge development, resource mobilisation, and entrepreneurial experimentations was critical in achieving technological self-reliance. KAERI was designated as the main contractor of NSSS design for the construction of Hanbit 3 and 4, because of all the key actors in the industry KAERI had the best R&D capability to absorb the NSSS design technology (Sung and Hong, 1999; MOST, 2007). KAERI dispatched its 200 scientists and engineers to CE in the U.S. (late 1986 to mid-1989) to acquire NSSS design technology. Beyond the learning of 'know-how' from CE, KAERI put great effort into learning the 'know-why', by organising regular seminars amongst

KAERI engineers, networking with CE engineers to acquire tacit knowledge, and documenting NSSS design verification in Korean (MOST, 2007). KEPCO fully sponsored the cost of dispatching KAERI engineers and its own engineers (1000 people) for NSSS design verification. The cost accounted for more than half of KEPCO's R&D expenditure (Sung and Hong, 1999).

As a result, Korea internalised the NSSS design technology at 1000 MWe by constructing Hanbit 3 and 4 in the mid-1990s, grounded in CE's System 80, thereby achieving technological self-reliance. In the late 1990s, Korea repeated the design and construction of ten NPPs.⁴ It also developed its own brands using NSSS design technology, including Korea Standard Nuclear Power Plant (KSNP), Optimized Power Reactor (OPR) 1000 (MWe), and Improved OPR 1000 (see Table 2). Moreover, the successful formation of an NPP market led by the government facilitated intensive knowledge development, given the maturity and the large scale (10 GWe) of the industry. After receiving NSSS design technology from KAERI, KEPCO E&C, and Doosan participated in the NPP construction as prime contractors since the Hanbit 5 and 6 and gradually improved the capability related to safety and efficiency in power generation, reliability, effective maintenance, and reduction of the construction cost of the last four NPPs: Shin-Kori 1 and 2 (2007) and Shin-Wolsong 1 and 2 (2008). The involvement of foreign sub-contractors in the review and consultation of projects significantly declined, and the localisation rate in engineering, equipment procurement, and construction reached about 80% in 2008 (Table 2).

After becoming technologically self-reliant, the key actors (i.e., KHNP, KEPCO, KEPCO E&C, KAERI, and Doosan) engaged in entrepreneurial experimentation to develop a completely indigenous technology Advanced Power Reactor (APR) capable of generating 1400 MWe (hereafter APR 1400). The purpose of developing the APR 1400 was to build NPPs that comply with international safety standards (Park and Chevalier, 2010) and are highly efficient because of their high capacity (1400 MWe) and an extended service time (60 years) as a base-load power generator so as to respond to growing electricity demand in Korea (Choi et al., 2009; see Fig. 4). Also, the government and the key actors had achieved a strong consensus on the technological and economic spillover effects of the APR 1400 on other related industries, such as the equipment sector (Hong, 2016). Under the government's long-term resource mobilisation of R&D (USD 200 million in seven years) (Son and Choung, 2014), the key actors developed the APR1400 in 2002 and installed it at Shin-Kori 3 and 4 and Shin-Hanul 1 and 2 (Table 2). With this entrepreneurial experimentation, Korea achieved a 100% localisation rate in the construction of Shin-Hanul 1 and 2.

5.3. From technological self-reliance to a global exporter since 2010

Even after achieving technological self-reliance in the early 2000s, Korea faced legitimacy challenges from the public. The international anti-nuclear movement since the late 1980s triggered a decrease in moral legitimacy in Korea (Jasanoff and Kim, 2009; Renn, 1990). Also, the Korean government's ineffective efforts to identify disposal sites for low- and medium-level radioactive waste further damaged the industry's legitimacy. Over 20 years (1986–2005), nine attempts were made and failed, which significantly reduced the legitimacy of nuclear power industry (Choi et al., 2009; Jasanoff and Kim, 2009; see Table 5). The public desire for 'Atoms for National Development and Security' had diminished. Instead, environmental groups and anti-nuclear activists began to challenge the government's plan for NPP expansion (Jasanoff and Kim, 2009; Valentine and Sovacool, 2010).

To respond to these challenges, the Korean government established the Korea Nuclear Energy Foundation (KNEF) in 1992 by mobilising financial resources (on average USD 5 million per year) (Chung and

Kim, 2018; Jasanoff and Kim, 2009). The KNEF was involved in managing public relations, advertising, and delivering education programmes to address this decreased legitimacy. Despite its efforts, it was almost impossible to stop the expansion in the anti-nuclear movement in Korea. As a result, the Korean government had difficulty in selecting new NPP construction sites, thereby inevitably delaying the construction of Hanbit 5 and 6 (1997) for more than a year (Park, 1992; Valentine and Sovacool, 2010). Subsequently, the government designed long-term plans to invest in electricity generation that reduced the proportion of nuclear power in the long run (see Fig. 6).

To cope with the decreased moral legitimacy in the domestic market, the key actors tried to export their technology (OPR1000 and APR1400), with government support since the late 1990s (Berthelemy and Leveque, 2011; Hong, 2016; Jasanoff and Kim, 2009).⁵ At the time, the global nuclear power market began to grow after a long silence, as emerging countries experienced rapid growth in their demand for electricity corresponding to their economic growth (IAEA, 2018; Wade and Walters, 2011), as shown in Fig. 6, Fig.7. In other words, economic growth in emerging countries created favourable conditions for Korea to export its technology. Accordingly, the country aggressively pursued export sales of its reactors, equipment, and design and maintenance services to China and other emerging countries in Southeast Asia and Eastern Europe (Jasanoff and Kim, 2009).

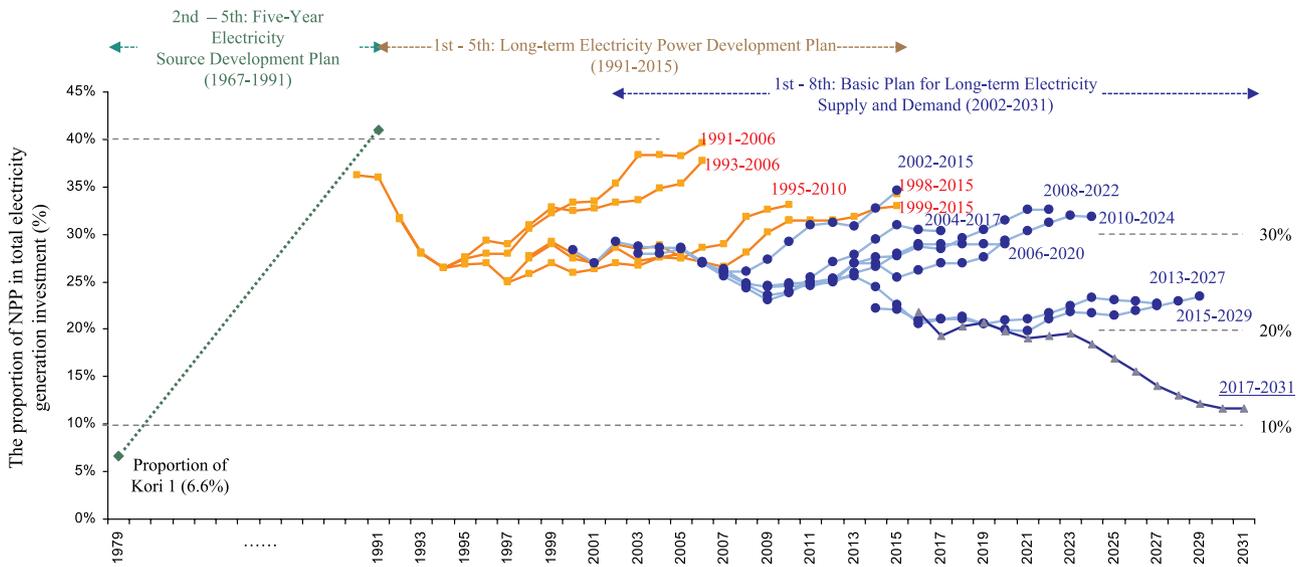
In the late 2009, KEPCO won a USD 20.4 billion turnkey contract to develop four NPPs (Barakah 1–4, constructed since 2012) with the APR1400 for the United Arab Emirates (UAE) after competing against a U.S.-Japan joint consortium (GE and Hitachi) and a French consortium (AREVA). Winning the contract enabled Korea to come the sixth NPP exporter in the world (Hindmarsh and Priestley, 2015) due to the cost advantage of the Korean NPP with its excellent operating performance and competitive pricing against other forerunners and reputation earned from other construction projects by Korean firms in the Middle East with on-time delivery. In addition, strong support by the Korean government via mobilisation of attractive project financing terms and military assistance contributed to its winning the contract (Berthelemy and Leveque, 2011; Kane and Pomper, 2014).

Notably, the resource mobilisation by the key Korean industrial actors to offer education and training programmes to the UAE was also critical in winning the contract (Holt, 2010). As with Korea's experience in the late 1980s, the declining industry legitimacy of the nuclear power industry in Korea created favourable conditions for the UAE to access a forerunners' knowledge base. With the strong quest by the UAE to internalise knowledge, Korea offered it the co-establishment and operation of nuclear engineering departments and collaborative research programmes (Khalifa University). Korea also supported training programmes for the construction, operation, maintenance, and safety regulatory personnel of the Emirate Nuclear Energy Corporation (ENEC) and the Federal Authority of Nuclear Regulation (FNAR) in the UAE. The chairman of ENEC stated that Korea's dedicated resource commitment and knowledge transfer was another important reason for choosing it over the other bidders (ENEC, 2009).

Furthermore, KEPCO's previous entrepreneurial experience in foreign market development through the Korean Peninsula Energy Development Organisation (KEDO) project to construct two OPR 1000 NPPs in North Korea was critical in winning the contract in the UAE. With the KEDO project, the government endeavoured to repair industry legitimacy by emphasizing that the industry can contribute to peace and prosperity on the Korean Peninsula (Jasanoff and Kim, 2009). Accordingly, the Korean government offered to cover 70% of the NPP construction cost for the KEPCO's KEDO bid. To prepare the bid for the project, KEPCO prepared all the documents in English to meet the

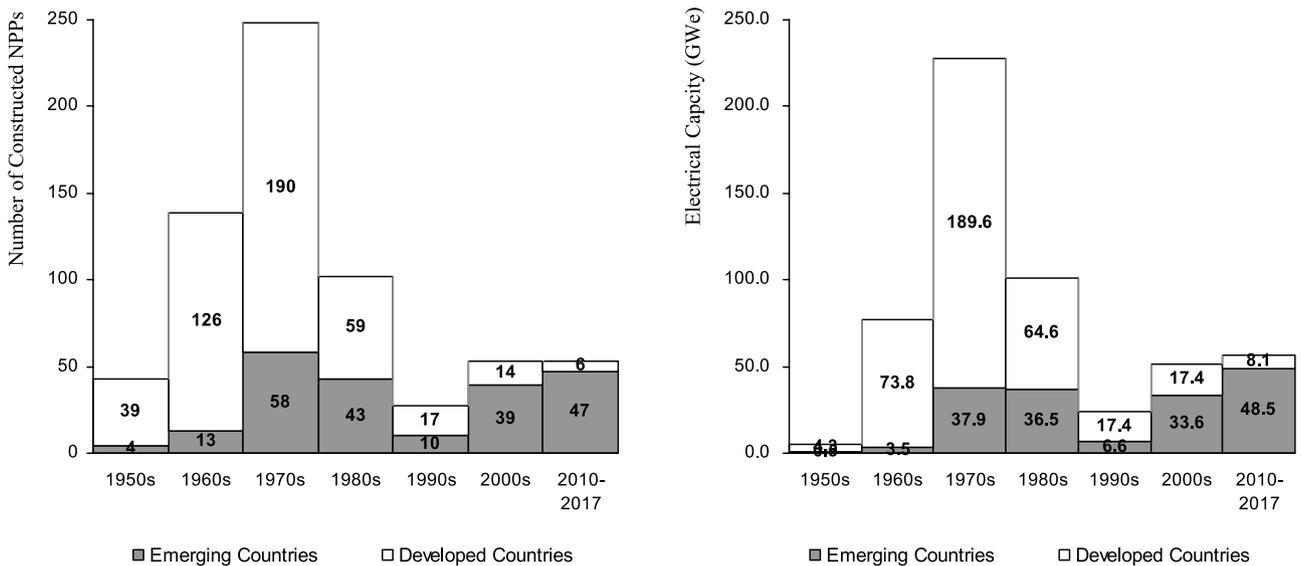
⁴ The ten NPPs are Hanul 3 and 4, Hanbit 5 and 6, Hanul 5 and 6, Shin-Kori 1 and 2, and Shin-Wolsong 1 and 2

⁵ For the purpose of foreign market development, KEPCO and DHIC renamed their brand from KSNP to OPR 1000



Source: Authors' analysis based on Hong (2016), Electric Power Statistics Information System (EPSIS) and the historic announcement of the Korean government's 'Five-Year Electricity Source Development Plan (2nd to 5th)', 'Long-term Electricity Power Development Plan (1st to 5th)', 'Basic Plan for Long-Term Electricity Supply and Demand (1st to 8th)'.
 Note: NPP construction was included from the second 'Five-Year Electricity Source Development Plan (1967-1971)'.

Fig. 6. Korean government's investment plan for NPP-based electricity generation.



Source: Authors' analysis based on Nuclear Power Reactors in the World (2018) by IAEA, accessed in May 2018.
 Note: The number and electrical capacity of NPPs in a specific period is calculated by considering the construction start year.

Fig. 7. Transition in the world NPP market: From developed to emerging countries.

international requirements for persuading KEDO's member countries, i.e., Japan, the U.S., the European Union, Australia, and others. Even though the project, initiated in 1996, eventually fell apart in 2006 because of the political tension over North Korea's nuclear weapons (Takeda, 2005), it was the first overseas project for KEPCO as a prime contractor in NPP construction.

After winning the UAE contract, the Korean government announced a long-term plan to nurture the nuclear power industry as a core export industry and to capture 20% of the global nuclear power market by 2030 (Berthelemy and Leveque, 2011; Holt, 2010; Kane and Pomper, 2014). To implement the plan, the government mobilised the national budget in establishing a Nuclear Powers Cooperation Division in the Ministry of Trade, Industry, and Energy and moved the export function of KEPCO to KHNP (Korea Hydro & Nuclear Power) for

systematic development of the foreign market. The resource mobilisation efforts in the nuclear power industry also led to the establishment of seven new nuclear engineering departments at universities between 2010 and 2015.

However, since the explosion of the Fukushima Daiichi Nuclear Power Plant in Japan in 2011, Korean perceptions of the nuclear power industry seem negative, especially from a cognitive perspective (Chung and Kim, 2018; Kim et al., 2013). Even though the two NPPs under construction, Shin-Kori 5 (2017) and Shin-Kori 6 (2018), succeeded in gaining moral legitimacy thanks to the efforts of a publicity campaign and social activists who played an important role in encouraging a favourable public opinion in 2017 (Shin-Kori 5 and 6 Public Opinion Committee, 2017), Koreans no longer perceive nuclear power as a legitimate electricity source (Chung and Kim, 2018).

Table 3
Summary of findings.

	1st Evolution (from ‘Turnkey’ to ‘Non-Turnkey’ importer)	2nd Evolution (from ‘Non-Turnkey’ importer to technological self-reliance)	3rd Evolution (from technological self-reliance to the global exporter)
<i>Exogenous Windows of Opportunity</i> <i>Changes in Forerunner’s Industry Legitimacy:</i>	<ul style="list-style-type: none"> ■ Increase (+) - Atoms for Peace 	<ul style="list-style-type: none"> ■ Decrease (-) - Safety concerns derived from two critical accidents (Three Mile Island and Chernobyl) and transnational anti-nuclear movement - Lack of economic feasibility due to efficient gas-fired power plants 	
<i>Endogenous Windows of Opportunity for Latecomer’s Industry Formation</i> <i>Creation of Legitimacy</i>	<ul style="list-style-type: none"> ■ Increase (+) - Atoms for National Development - National and Energy security 	<ul style="list-style-type: none"> ■ Increase (+) - Self-reliance on NSSS design technology and political interference from U.S. 	<ul style="list-style-type: none"> ■ Decrease (-) - Influenced by the transnational anti-nuclear movement - Social conflict in selecting low and intermediate level radioactive waste (LILW) storage sites derived from policy failure
<i>Resource Mobilization</i>	<ul style="list-style-type: none"> ■ Included NPP construction in the ‘Second Five-year Economic Development Plan’ (1967-1971) ■ Established Ministry of Energy and Resources for the nuclear power industrial policy (1977) 	<ul style="list-style-type: none"> ■ Organized EPGCC arranged by Ministry of Energy and Resources (1985) and suggested ‘standardisation’ of NPPs ■ Government R&D for developing KSNP, OPR 1000, and APR 1400 ■ KEPSCO’s investment in NSSS design verification 	<ul style="list-style-type: none"> ■ Established KNEF (1992) and implemented a government’s budget for enhancing the legitimacy of nuclear power industry (not successful) ■ Provision of attractive project financing and military assistance from government ■ Support the development of education and training programs for UAE national talent ■ Korean government decided to cover 70% of NPP construction expense in KEDO project for enhancing the legitimacy of nuclear power industry (not successful)
<i>Knowledge Development</i>	<ul style="list-style-type: none"> ■ Acquire U.S. technology: Westinghouse ■ Increase in localization rate in NPPs - Enhanced from 8-13% (Turnkey import) to 29-40% (Non-Turnkey imports) ■ Established industrial alliance and academic society - Korean Nuclear Society (1969) - Korean atomic industry forum (1972) 	<ul style="list-style-type: none"> Acquire core technology of U.S.: Combustion Engineering Develop an original NSSS technology: KSNP and OPR 1000 in the late 1990s Increase in the localisation rate of NPPs - Enhanced from 75% (KSNP) to 100% (APR 1400) 	
<i>Market Formation</i>	<ul style="list-style-type: none"> ■ Construction of the first NPP: Kori 1 (1972) ■ Construction of the six NPPs after the first oil shock (1973): Kori 2 and Wolsong 1 (1978), Kori 3 and 4 (1980), Hanbit 1 and 2 (1981) ■ Simultaneous construction of the six NPPs for Non-Turnkey imports: Kori 3 and 4 (1980), Hanbit 1 and 2 (1981), and Hanul 1 and 2 (1983) 	<ul style="list-style-type: none"> ■ Construction of two NPPs with a compulsory technology transfer condition: Hanbit 3 and 4 (1990) ■ Simultaneous construction of ten NPPs to achieve technological self-reliance (KSNP, OPR 1000, improved OPR 1000), so called ‘standardisation of NPPs: Hanul 3 and 4 (1993), Hanbit 5 and 6 (1997), Hanul 5 and 6 (2000), Shin-Kori 1 and 2 (2007), and Shin-Wolsong 1 and 2 (2008) 	<ul style="list-style-type: none"> ■ Efforts to develop foreign market
<i>Entrepreneurial Experimentation</i>	<ul style="list-style-type: none"> ■ Entry from local entrepreneurial firms in civil engineering (construction) and equipment manufacturing ■ Co-established Korea Nuclear Engineering to enhance capability for architectural engineering (1976) 	<ul style="list-style-type: none"> ■ KAERI’s efforts for the learning of CE’s NSSS technology ■ Develop a completely indigenous NSSS technology: APR 1400 	<ul style="list-style-type: none"> ■ Utilize the experience in KEDO project as the prime contractor (for NPP construction under a turnkey contract)

According to a national survey on NPPs by KNEF in 2016, the proportion of citizens who hold a negative perception of NPP expansion (61.3%) was the highest since the survey was first conducted in 1995 (KNEF, 2017). In May 2017, the newly elected president, Moon Jae-In, declared a halt in the construction of additional nuclear power plants and a steep decrease in the proportion of nuclear power used in the generation of electricity (see Fig. 6).

5.4. Summary of findings

Our longitudinal analysis shows that transnational industry legitimacy dynamics and domestic industry formation efforts influenced

Korea’s catch-up in nuclear power industry (see Table 3). First, during the period from ‘turnkey’ to ‘non-turnkey’ imports (late 1960s-early 1980s), the increase in forerunners’ industry legitimacy (‘Atoms for Peace’) provided an exogenous window of opportunity for latecomers to access forerunners’ knowledge base. In addition, with the increase in industry legitimacy in Korea (‘Atoms for National Development and Energy Security’), the Korean government mobilised resources, developed knowledge, and formed a market that played a critical role in the country’s becoming a ‘non-turnkey’ importer.

Second, during the period from ‘non-turnkey’ imports to technological self-reliance (the late 1980s to the late 2000s), the decline in the forerunner’s industry legitimacy provided a critical exogenous window

for Korea to acquire core technology from forerunners in a transnational context. Also, domestically increased legitimacy for becoming technologically self-reliant enabled key actors to endogenise windows of opportunity through market formation and resource mobilisation by the Korean government. KAERI and KEPCO also contributed to endogenising windows of opportunity through knowledge development, resource mobilisation, and entrepreneurial experimentation. As a result, Korea became technologically self-reliant in 1000 MWe NPP (KSNP and OPR 1000) and further mobilised substantial resources to develop a completely indigenous NPP with 1400 MWe (APR 1400) as an entrepreneurial experimentation.

Interestingly, in the third phase of being a global exporter (since 2010), the decrease in domestic legitimacy of the nuclear power industry that originated in the forerunner's anti-nuclear movement and the policy failure of the Korean government in selecting radioactive waste disposal sites led Korea to seek opportunities overseas. With the increase in the legitimacy of the industry in emerging countries, resource mobilisation by the Korean government (project financing terms and military assistance) and the Korean key actors' advanced technological capability (reputation in the Middle East, education and collaborative research programmes, and previous entrepreneurial activities in KEDO) contributed to KEPCO's winning of turnkey contracts for constructing four NPPs in the UAE.

6. Discussion and conclusion

6.1. Theoretical contributions and implications

Prior catch-up studies focused on either exogenous or endogenous windows of opportunity (Lee and Ki, 2017; Vértesy, 2017; Yap and Truffer, 2019). We advance these studies by explaining that whereas exogenous windows of opportunity for latecomers stem from the changes in a forerunner's legitimacy in a transnational context, endogenous windows of opportunity are exploited by latecomers in their domestic context. By distinguishing between exogenous and endogenous windows of opportunity (Lee and Malerba, 2017; Miao et al., 2018) and proposing a framework to develop a more comprehensive explanation, this study makes several theoretical contributions.

First, it advances our understanding of the new drivers of exogenous windows of opportunity by considering changes in the forerunner's industry legitimacy. While previous studies on the rise of latecomers focused on the economic aspect of institutional forces (e.g., import duties, R&D subsidies, technology standardization and adoption), our analysis shows that the sociological perspective of institutional impacts (i.e. legitimacy) is also an important element for latecomers to grow in a challenging environment (DiMaggio and Powell, 1983; O'Kane et al., 2015; Scott, 2001). Moreover, whereas the legitimacy of organisations has received much attention in the literature (Deephouse and Suchman, 2008), we extend these studies by investigating legitimacy at the level of a specific technological field in an industry (Aldrich and Fiol, 1994; Bergek et al., 2008; Geels and Verhees, 2011; Zhang and White, 2016).

Second, combining insights from catch-up theory (Lee and Malerba, 2017) and the TIS framework (Bergek et al., 2008; Binz et al., 2014; Hekkert et al., 2007; Yap and Truffer, 2019), we show how actors in a latecomer context can strategically take advantage of the six core system functions for endogenisation of windows of opportunity and successful industry formation. Whereas prior studies on CoPS focused on the role of government in engineering policies to support technology development (Kiamehr et al., 2013; Naghizadeh et al., 2017; Park, 2012), our analysis provides a systemic perspective on industry formation not considered in conventional studies on latecomers' CoPS (Safdari Ranjbar et al., 2018; Yap and Truffer, 2019). Therefore, we contribute to understanding of the interplay between government and key actors in the industry in endogenising windows of opportunity.

Lastly, prior studies on latecomers' CoPS focus on specific points in

time, such as the entry stage or the maturity stage, when latecomers penetrate foreign markets (Kiamehr et al., 2015; Vértesy, 2017). As a result, we lack understanding the challenges and remedies of latecomer's catch-up in each stage (e.g. turnkey importer, self-reliant producer, and exporter) (Lee and Yoon, 2015; Miao et al., 2018). As part of determining a holistic process of latecomer catch-up, our analysis documents the trajectory from a latecomer's inception to the point when the latecomer becomes an indigenous developer and exports a turnkey CoPS. In sum, we advance understanding of latecomers' technological advancement trajectory over time by considering the combination of changes in a forerunner's industry legitimacy and a latecomer's efforts to endogenise windows of opportunity.

6.2. Practical implications

We also provide valuable implications for policy makers and managers in latecomers' CoPS industry. It is important to recognise the changes in a forerunner's industry legitimacy and to understand the implications on latecomers' access to an external knowledge base. In addition, consistent with prior studies on industrial development policies in East Asia, particularly for CoPS, our findings show that CoPS were primarily led by governments especially during the inception period (Lee and Ki, 2017; Lee and Yoon, 2015; Park, 2012). More importantly, we emphasise that the government can act as an orchestrator to foster interplay between key actors in the successful formation of an industry. During the period of developing new industries and rapidly catching up, some East Asian countries were governed under a dictatorship (e.g. South Korea) or even had a communist government (e.g. China) (Hahm and Plein, 1995; Kim, 2004; Motohashi and Yun, 2007), so government leadership in industry formation is only to be expected.

Although our analysis shows that government played a key role in industry formation and its subsequent development, countries with different institutional settings may adopt a different approach in which such industry information is led by entrepreneurs, interest groups, and professional communities (Bergek et al., 2008; Hekkert et al., 2007; Wirth et al., 2013). In fact, our analysis partially confirms this view by showing the significant role played by key industrial actors in developing foreign business opportunities (i.e. the UAE) that correspond to the substantial decrease in Korea's nuclear power industry legitimacy. In particular, it is important to note the difficulties in addressing such a legitimacy crisis by relying solely on government efforts (Suchman, 1995). In fact, the majority of Korea's industry legitimacy crisis originated in government failure (e.g. in selecting radioactive waste disposal sites) (Choi et al., 2009; Jasanoff and Kim, 2009; see Table 5), but industrial actors can spontaneously work together to develop business opportunities outside their home market to cope with the legitimacy crisis in their domestic market.

6.3. Limitations and future research avenues

Naturally, our study is not without limitations. Our analysis focusing on the Korean nuclear power industry may raise issues related to its generalisability. Nevertheless, the selection of our case is justified, because the nuclear power industry with its power generation technology is a common case of CoPS (Davies and Brady, 1998; Hobday, 1998; Markard and Truffer, 2006; Miller et al., 1995).

In addition, Korea is the only country in the world to start developing its nuclear power industry as a latecomer by importing 'turnkey' nuclear power and eventually became the sixth country in the world (after the U.S., Russia, Canada, France, and Japan) to export nuclear power plant construction (Hindmarsh and Priestley, 2015). In fact, Korea became capable of not only developing and constructing the sixth-largest fleet of nuclear reactors in the world but also constructing four nuclear reactors in the UAE under a USD20 billion contract.

Furthermore, our findings are generalisable to other latecomers' CoPS industry. For example, Iran's land-based gas turbine industry

Table 4

Terms of technology transfer agreement between CE and KEPCO.

Source: Adapted from [Ahn and Han \(1998\)](#), [Sung and Hong \(1999\)](#), [Hong \(2016\)](#), and authors' analysis based on interviews.

Channels	Detailed terms and condition
Technological Documents	<ul style="list-style-type: none"> ■General documents: licensing, quality assurance, and procedures ■Reference documents: design (CAD program), calculation notes, manuals, design drawing and specification, and procedure ■Delivery schedule: within 6 months after the contract
Computerised Design Code	<ul style="list-style-type: none"> ■Installation, verification and validation code, source programs, manuals, and QA verification documents ■Delivery schedule: within 1 year after the contract
Patent Licensing	
Job Training and Participation (Joint Design and Development)	<ul style="list-style-type: none"> ■On the job training (Joint Design): co-participation in NSSS design between CE (technology donor) and KAERI (technology recipient) in order to save time to design as well as accelerate technological learning by Korea. -No extra cost for training engineers -CE takes all responsibility for and guarantees the deliverables of the joint design -Delivery schedule: within three years after the contract ■On the job participation (Joint Development): perform NSSS design on NPP construction site with review and consultation with CE -Delivery schedule: During the successive NPPs construction, however, the degree of review and consultation were much less significant

benefited from abrupt changes in forerunners' institutional environment. As the U.S. sanctioned Iran, which limited U.S. firms' transactions with Iranian counterparts, European firms (e.g. Siemens and Ansaldo) emerged as key players in transferring technology to Iran (see [Kiamehr et al., 2015](#); [Majidpour, 2016, 2017](#)). The sanctions also strengthened the determination of the industry authorities in Iran to achieve technological self-reliance ([Majidpour, 2017](#)). The Iranian government created legitimacy in the domestic context by establishing and supporting a state-owned enterprise (i.e. Mapna) to achieve catch-up ([Kiamehr et al., 2013; 2015](#)).

Moreover, Korea's catch-up in mobile communication systems was

initially triggered by a forerunner's strategic decision to legitimise the use of military-based technology for commercial purposes ([Lee and Lim, 2001](#); [Park, 2012](#)). As a result of this change in the forerunner's environment and Korea's efforts to achieve technological self-reliance via creating R&D programmes and forming a domestic market based on technology standardisation, Korea was able to acquire core technology from the U.S. firm Qualcomm and become a leader in the global telecommunication market ([Lee and Lim, 2001](#); [Park, 2012](#)).

Despite the generalisability of our findings across different countries and industries, we encourage researchers to use our analytical approach and framework in a wide variety of catch-up and leapfrogging contexts.

Table 5

Selection of low and medium-level radioactive waste disposal sites in Korea.

Time Line	Main activity and result of endeavour
1st Endeavour (5/1986 - 3/1989)	<ul style="list-style-type: none"> ■Implemented consultation on the environmental analysis for candidates for LILW sites ■Selection of the three candidate sites by the central government (Uljin, Yeongdeok, and Pohang) ■Disclosed by National Assembly and residents staged protests of the decision: Government abandoned implementation
2nd Endeavour (9/1990 - 6/1991)	<ul style="list-style-type: none"> ■Selected Anmyon Island as the sole LILW sites and formulated a plan to establish a branch of KAERI in the sites in secrecy. ■Media disclosure followed by serious demonstrations by residents: Government announced the end of the endeavour.
3rd Endeavour (11/1991 - 3/1993)	<ul style="list-style-type: none"> ■Developed a new policy in which the central government lists candidates for LILW sites at first and designate LILW site based on voluntary hosting by the community. ■Planned to support the hosting community based on regional cooperation activities by the central government
4th Endeavour (11/1993 - 6/1994)	<ul style="list-style-type: none"> ■Residents of all seven potential sites staged protests: Government announced the delay of designation ■Enacted the Act for Promoting the Radioactive Waste Management and for Supporting the Communities Surrounding the Sites ■Created pro-nuclear force that supports the hosting of LILW sites and designated two communities as top priority (Uljin, Yangsan) ■Serious demonstrations led by anti-nuclear force in the two communities: Government withdrew the endeavour.
5th Endeavour (11/1994 - 12/1995)	<ul style="list-style-type: none"> ■Gulup Island with its small number of residents was selected as the sole candidate for LILW sites. ■Found that the island is geologically unstable (active fault): Government withdrew the endeavour. ■Changed the ministry in charge of the LILW sites from MOST to MOTIE
6th Endeavour (6/2000 - 7/2001)	<ul style="list-style-type: none"> ■Utilized resident-driven petition for hosting LILW sites via pro-nuclear force ■Failed to acquire support from local assembly and administration: The endeavour was aborted
7th Endeavour (12/2002 - 2/2003)	<ul style="list-style-type: none"> ■Implemented the designation of four potential sites and the creation of pro-nuclear force in parallel. ■All four sites opposed to the LILW: The endeavour was aborted
8th Endeavour (6/2003 - 2/2004)	<ul style="list-style-type: none"> ■Implemented local administration-driven petition for hosting LILW sites ■Governor of Buan applied for hosting of LILW sites without agreement with the local assembly. ■As a result of local voting, 91.% of residents opposed hosting LILW: The endeavour was aborted -Turnout Ratio (# of Voters): 72.0% (37,540)
9th Endeavour (2004.2. - 2005.11)	<ul style="list-style-type: none"> ■Built competition amongst local administrations while maintaining local administration-driven petition for hosting LILW sites ■Required local assembly's agreement for petition ■Enacted the Special Act for Hosting Community of LILW Sites ■Implemented competitive bid amongst four communities that applied the hosting based on local voting: Kyongju was determined as the hosting community for LILW sites -Kyongju: 85.5% in favour with 70.8% turnout (147,636 voters) -Gunsan: 84.4% in favour with 80.2% turnout (138,192 voters) -Yeongdeok: 79.3% in favour with 80.2% turnout (30,107 voters) -Pohang: 67.5% in favour with 47.7% turnout (178,586 voters)

Data Source: [Dong-A Daily \(2004\)](#), '91.8% of Residents in Buan opposed to host Radioactive waste disposal sites'; [Hong \(2016\)](#); Korea Radioactive Waste Agency (2018), 'The history of low and intermediate level waste (LILW) storage sites'; MOTIE (2005), 'Kyongju was selected as a radioactive waste disposal site with 89.5% in favor'.

In particular, we call for more research in the context of leapfrogging to achieve more sustainable industrial structures. Such a transitional context deserves further attention, as sustainable industries require latecomer countries to consider a much broader set of strategies within their socio-technical systems (Schot and Steinmuller, 2018; Wirth et al., 2013; Yap and Truffer, 2019).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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