Received: 12 August 2019 | Revised: 1 October 2019 | Accepted: 2 October 2019

DOI: 10.1002/wene.366

FOCUS ARTICLE

WIREs ENERGY AND ENVIRONMENT WILEY

Assessing the impact of R&D policy on PV market development: The case of South Korea

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Funding information
Korea government (MOTIE), Grant/Award Number: 20188550000450

Abstract

The purpose of this article is to examine the Korean photovoltaic (PV) R&D strategy and its effectiveness in helping Korean manufacturer competitiveness. The article reviewed the Korean government's PV R&D funding from 2008 to 2017 and investigated the technology readiness levels of 298 R&D projects funded by the Korean government during the same period. It is found that the Korean government followed a two-track approach of nurturing commercialization technology to cope with rapid growth and volatility in the current global market. The effects of government support for market-ready and next-generation technologies in order to position the country in today's competition and to prepare it for "first mover" opportunities in emerging markets are considered. During 2008–2017, Korean manufacturers maintained a 7% of market share. Module prices, which were more than USD 6 per watt in 2000, fell to less than USD 1 in 2017. From a technical point of view, silicon-based modules have achieved world-class status in their efficiency. Performance of the country's nonsilicon technologies reached nearly 90% of the world's best nonsilicon products in the early 2010s, but recently, next-generation technology development is lagging. Despite Korean PV industry's achievements, it is unclear whether Korean government PV R&D strategy affected competitiveness. Since 2013, the Korean government has sharply cut PV R&D funding. Early growth may have been affected by government support, but recent growth may be driven by corporate strategies. A significantly higher level of R&D funding may be needed for Korea's next-generation technologies to capture "first mover" status.

This article is categorized under:

Energy and Climate > Economics and Policy
Photovoltaics > Economics and Policy
Energy Policy and Planning > Economics and Policy

KEYWORDS

energy policy, energy R&D, Korea solar policy, solar energy, solar markets

1 | INTRODUCTION

The global photovoltaic (PV) market grew exponentially in the last decade, with newly installed solar capacity exceeding 100 GW in the year 2018 (IEA PVPS, 2018). This was driven by individual countries' industrial policies which promoted the expansion of the PV market, and by global energy transition efforts to reduce greenhouse gas emissions to stop climate change (Avril, Mansilla, Busson, & Lemaire, 2012; Wang, Byrne, Kurdgelashvili, & Barnett, 2012).

Government R&D funds have been found by researchers to contribute to the popularization of solar PV energy through the improvement of efficiency and cost reductions (Byrne & Kurdgelashvili, 2011; IRENA, IEA, & REN21, 2018; Kharaji Manouchehrabadi & Yaghoubi, 2019).

A variety of literature has analyzed the effectiveness of PV R&D on making PV one of the most promising energy technologies in many regions. Several countries (including Germany, Japan, and the United States) have explored PV-related policies and technology development (Avril et al., 2012; Grau, Huo, & Neuhoff, 2012; Sahu, 2015; Taghizadeh-Hesary, Yoshino, & Inagaki, 2018; Yu, Popiolek, & Geoffron, 2016). Research findings show that R&D funding generated a noticeable impact on the PV market in China, Germany, and the United States (Byrne & Kurdgelashvili, 2011; Grau et al., 2012). Many of the studies in the field have applied patent analysis with the purpose of measuring global PV technology development (Breyer, Birkner, Meiss, Goldschmidt, & Riede, 2013; Liu et al., 2011; Sampaio et al., 2018). Breyer et al. (2013) applied a top-down approach to examine the effect of patents on global PV R&D investments. Significant growth in PV R&D investments, patent applications, and R&D headcounts were found to be correlated, which encouraged the PV market expansion and cost reduction.

An increasing number of studies of the PV industry in Korea address the current status and trend in PV technology, policy, market, and investment (Jo, Lee, Jeon, & Lee, 2009; Park, 2017; Woo, 2017). Several publications focus on government R&D to emphasize the role of the government in strategically vitalizing the Korean PV industry (Kim, Pang, Ahn, & Park, 2013; KISTEP, 2012; Son, Moon, & Ahn, 2015). Park, Cho, Byeon, and Cho (2015) analyzed the connectivity among different PV technologies to find ways of improving the efficiency of R&D investment. Their work linked research projects led by various government departments and joint research with leading countries in PV R&D and suggested their link can facilitate market development.

The purpose of this article is to identify Korean PV R&D strategy and to examine its effectiveness. We analyze diverse government documents including national PV R&D plans, industry data, and information on government funded R&D projects to identify various aspects of Korean PV R&D strategy and its effect on the Korean PV market and technology development. This study is different from existing research in that it conducts analyses of government funded PV R&D projects from 2008 through 2017 according to technology readiness level (TRL) and technology characteristics (silicon-based and nonsilicon-based). To date, TRL analysis on country-level PV R&D projects is not considered in existing studies. It will be beneficial in understanding Korea's PV technology maturity trend and the government's R&D investment strategy.

Section 2 reviews Korea's national PV R&D plans and summarizes their objectives and targets. Section 3 identifies the main characteristics of Korean PV R&D by analyzing government funded R&D projects. Section 4 examines whether the government's PV R&D strategy generated desired outcomes in solar economics and technology innovation. Section 5 discusses the future role of the country's PV R&D to support national and global commitments to build a carbon-free energy transition.

2 | KOREA'S NATIONAL PV R&D PLANS

Korean PV industry development has been led by two government interventions: (a) R&D planning to support technology development; and (b) solar energy deployment policies.

The Korean government's PV R&D investment started in 1988. By 2003, PV technology development started to be promoted under the government's master plan and independent budget program. The first master plan related to renewable energy technology development was established by article 5 of the Act on the Promotion of the Development, Use, and Diffusion of New and Renewable Energy[1] in 2003. The plan was set for a period of 10 years, to be renewed every 5 years. It targeted nurturing the PV industry as one of the country's major policy commitments. The main focus of technology development was put on low-cost manufacturing and thinnerizaiton technologies that would encourage Korean companies to successfully sell products at the global market.

After the renewal of the master plan in 2008, it was actually the first national plan which announced a national R&D investment roadmap encompassing both silicon and nonsilicon-based PV technologies. The Korean government declared its intention to lead PV R&D investment until it became marketable. The plan presented a three-phase PV technology development roadmap. In Phase I, the country would focus on technologies such as crystalline silicon solar cell process improvement, thin film silicon compound solar cell manufacturing technology, and an automated production process. The government's goal was to find ways to strengthen the competitiveness of silicon solar cell production. Dye-sensitized organic solar cell and quantum dot solar cells were presented as core technologies in the second (2011–2020) and third (2021–2030) phases. The country pursued the commercialization of PV technology in the short term and the development of strategic technology in the long run.

In 2011, the National Energy Technology Development Plan (2011–2020) was announced as a part of Korea's green growth initiative. Solar technology became the focus of the country's highest level of energy technology development plan (see article 11 of the Energy Act[2]). This plan intended to make Korea one of the top five manufacturers in the global green energy market by 2020. It concentrated on green energy among all energy sources, placing it at the forefront of the country's green growth initiative (Ha & Byrne, 2019). PV technology was selected as one of the key investment target technologies to develop a new export industry and growth engine for the economy. Compared to the previous plan, technology development targets became more specific and bolder. Two key principles of the government's R&D investment were: fast commercialization and the development of a priority for future strategic technologies. The previous plan had set timelines for next-generation technology development by phases, but actual R&D investment concentrated heavily on silicon PV, which had already achieved a near worldwide commercialization status. In contrast, the new plan emphasized innovative next-generation technologies. Of the seven focus PV technologies (crystalline silicon solar cell, silicon thin solar cell, CuInGaSe2 (CIGS) thin solar cell, building integrated photovoltaic (BIPV) module solar cell, dye-sensitized solar cell, organic solar cell, and concentrating PV module), five (CIGS thin solar cell, BIPV module solar cell, dye-sensitized solar cell, organic solar cell, and concentrating PV module) were seen as priorities for the future market.

The renewed National Energy Technology Development Plan (2014–2023) presented more detailed targets and programs to create businesses compared to the previous plans. This is shown in its objectives stated as "to increase the commercialization rate of technology by 10% and to achieve more than a 10% global market share." In order to meet these objectives, action programs were set up: (a) increase R&D investment for demonstration projects to facilitate the commercialization of source technologies; (b) provide market information and technology advice to government R&D fund recipients; and (c) promote breakthrough technologies for performance improvement, cost reductions, and early commercialization. The objectives and targets of this plan create a clear divergence from the previous ones. The 2011 plan emphasized basic and source technologies that would create first-mover advantage in the future market, while the new plan drew attention to creating business opportunities in the present market with developed technologies.

A comprehensive national renewable energy technology development plan has not been developed since the National Energy Technology Development Plan in 2014. Instead, the 2030 New Energy Business Diffusion Strategy announced by the Korean government in 2015 included a technology development strategy by energy source. The strategy presented two solar material targets. One target was to accomplish 35% reduction of module production cost per unit power for silicon solar cell. The other was to develop next generation solar cells replacing silicon solar cells. According to these two targets, the government intended to focus silicon-based PV R&D on medium and small companies' bottleneck technology and to strengthen the emerging PV technology. The strategy stressed R&D investing in the improvement of the cost competitiveness of silicon solar cell systems in order to cope with global market challenges, especially in the plethora of Chinese low-price products supply. As the focus on future technologies became more intensified, the government declared that current funding of the silicon-

TABLE 1 Korean photovoltaic R&D plans and their objectives for the past 10 years

Year	Plan	Objectives
2008	Basic Plan for New and Renewable Energy Technology Development, Use, and Diffusion (2009–2030)	Develop ultra-low price and high-efficiency solar cell
2011	National Basic Plan for Energy Technology Development (2011–2020)	Jump to one of the top five manufacturers in the global green energy market Move up the export timing of PV products by achieving technology independence and price competitiveness
2014	National Basic Plan for Energy Technology Development (2014–2023)	Strengthen innovation-driven and commercialization-based technology development Increase the commercialization rate of technology by 10%. Achieve more than 10% of global market share
2015	2030 Energy New Industry Proliferation strategy: Five-year Basic Plan for Achieving Future Vision of 2030	Differentiate technology development strategy by market maturity (Future Market) Next-generation solar cell: Securing core technologies (Matured Market) Silicon solar cell: Competing in price/quality (efficiency)

based PV R&D would transfer to future PV technology R&D at the end of the ongoing projects. Table 1 summarizes the Korean government's PV R&D strategies which have constituted a part of comprehensive energy R&D plans during the last 10 years.

In summary, the Korean government intends to use a strategy in PV technology development by balancing R&D investment between the silicon-based PV market and the future nonsilicon-based PV market.

3 | THE ACTUAL DEVELOPMENT OF THE KOREAN SOLAR PV R&D SYSTEM

To reach these findings, we analyzed 298 solar PV R&D projects funded by the Korea Ministry of Trade, Industry, and Energy (MOTIE) during the period of 2008 through 2017. A total of 833 million USD was invested into the 298 projects. 577 million USD came from government support. Private companies which won government grants provided additional 256 million USD of matching funds. Among the 298 projects, 60 were dedicated to developing original technology. Grant winner companies created partnerships with universities or/and public research institutes for carrying out R&D.

The year 2008 was a breakthrough for the Korean PV industry support policy and it coincided with the launch of new political leadership, the Lee Myung-Bak Administration, which promoted Green Growth as the country's flagship policy. Korea's renewable energy R&D geared up as an independent budget program. A governance system was set up for the decision making and implementation of solar PV R&D. Korea Energy Technology Evaluation and Planning (KETEP) was established by the Framework Act on Energy in order to promote energy R&D in a more strategic way to cope with global market and with long-term vision. A solar PV Program Director (PD) was first appointed among private sector experts and he/she was supposed to coordinate PV R&D policy and R&D fund implementation reflecting the global market and R&D trend.

An analysis of 298 the projects has identified two key features of the Korean solar PV R&D. One feature is PV technology development is led by government funding. Also, the Korean government has taken a strategy of balancing investments between present and future technology designs.

3.1 | Government-led PV technology development

Korean PV technology development has mainly depended on government fund (Refer to Figure 1b). During the time when the global PV market was rapidly growing as a result of strong renewable energy deployment policy support in a number of countries (Goodrich, Powell, James, Woodhouse, & Buonassisi, 2013; Hoppmann, Peters, Schneider, & Hoffmann, 2013; Lund, 2009; Zhang, Andrews-Speed, Zhao, & He, 2013), the Korean government decided to foster the PV industry that could be competitive in technology, could realize economies of scale, and could supply the needed materials and production equipment (Kim et al., 2013). Investment in R&D has been one of the major means to facilitate the renewable energy industry and its deployment. Figure 1 shows that Korea maintained a relatively high ratio of R&D investment to gross domestic product (GDP) in the field of solar PV compared to other leading countries (IEA PVPS, 2009–2018)—see panel (e). The Korean government provided solar PV R&D funds between 0.005 and 0.01% of GDP during the period of 2008 through 2017. During the same period, government funding by Japan and the United States for PV R&D was below 0.002% of GDP (see panel (e) of Figure 1).

As shown in Figure 1b, during the period of 2008 through 2012, the government PV R&D budget continued to increase. A decline began from 2013 and it matches the price fall of PV products (see Figure 1d) due to the growth in Chinese manufacturing that lowered costs and put downward pressure on module prices. The Korean PV industry that just initiated mass production was adversely affected by abrupt price decreases and dramatic cuts in PV R&D, and a number of companies had to close their doors (Noh, 2014).

The government continued to reduce the size of solar PV R&D funding. As shown in Figure 1c, during 2013 and 2014, out of the total renewable R&D investment, the PV R&D portion noticeably decreased contrary to the increased growth of renewable R&D. The PV R&D budget has so far not recovered despite the revitalization of the global PV market. A sharp shrinkage in renewable R&D investment was caused by the new government led by President Park Keun-Hye (Park & Jung, 2016). Solar PV R&D investment fell in amount remained beat after 2015 (compare panels (a) and (c) in Figure 1).

During the PV market recession, the Korean PV industry was restructured and achieved scale of economies centered on a very few large conglomerates which could face fierce market competition (Yang, 2012). After 2015, government funding for PV R&D stayed heavily constant and investment by companies followed suit (Figure 1b). Government funding allocated

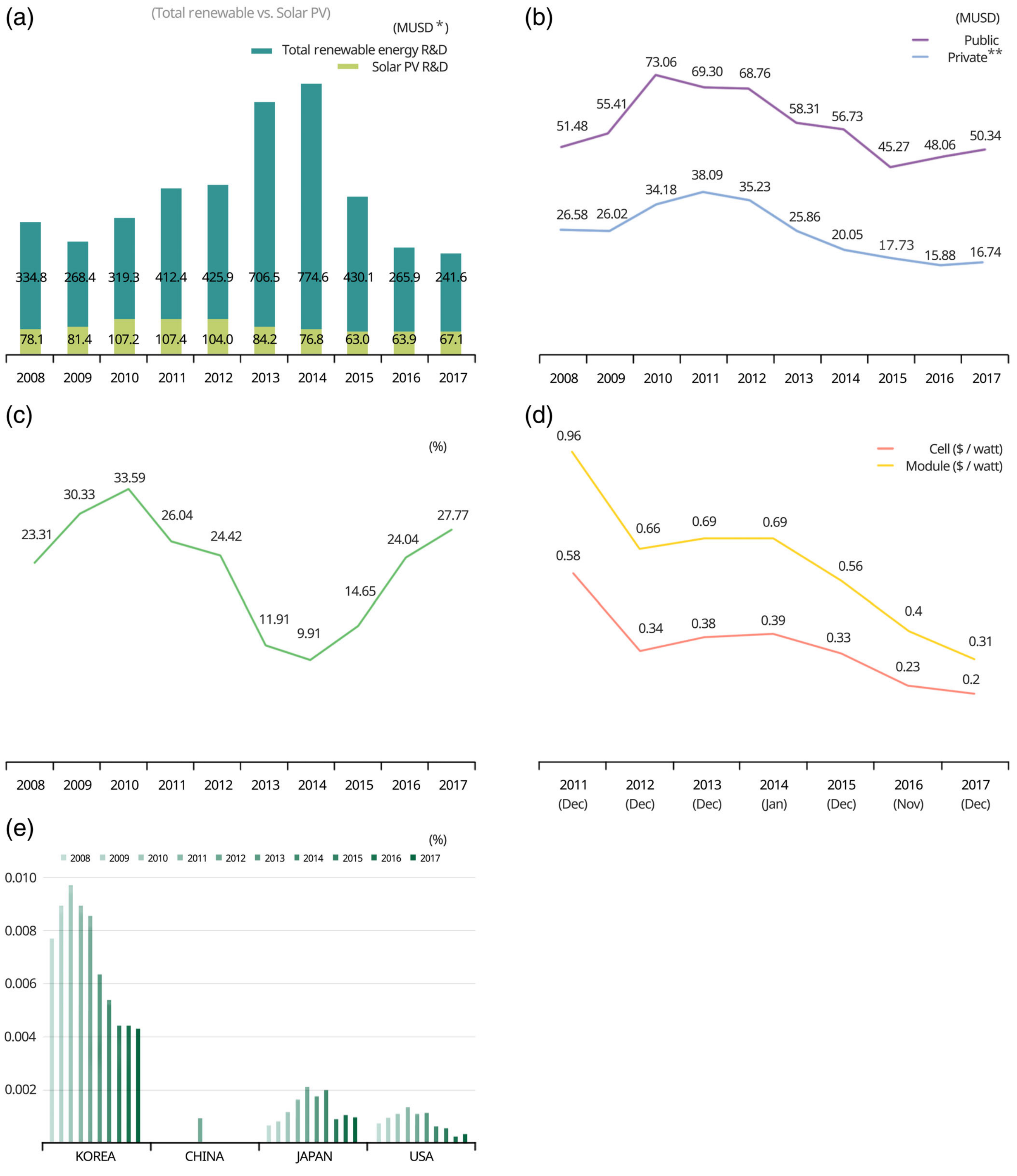

FIGURE 1 Korean solar photovoltaic (PV) R&D investment and PV products price trends. (a) Renewable energy R&D investment (Korea). (b) Public and private PV R&D investment (Korea). (c) Share of solar in renewable energy R&D investment (Korea). (d) Global price trend of PV products. (e) Solar PV R&D ratio to gross domestic product (GDP) by country. *Data*: The Korea MOTIE, IEA PVPS (2009–2018; IEA PVPS, 2007a, 2008a, 2009a, 2010a, 2013a; IEA PVPS, 2013b, 2014a), PV insights,[7] World Development Indicators.[8] *In panel(a), MUSD represents million US dollar. **Private investment is the matching funds from companies needed to receive government grants

more grants to medium- and small-scale businesses than to conglomerates.[3] It was possible because large Korean PV enterprises became competitive at the global market with technical advantage (Kang, 2019). In sum, while the market for PV resumed its growth pattern after 2015 but PV R&D did not. Although the share of PV to non-PV funding increased, this can be misleading. In fact, funding for innovation in both sectors decreased (until 2017), but non-PV funding fell ever faster. This led to deceptive increase in the share of PV R&D even though the actual amount of grant support decreased and stayed least.

3.2 | Balancing R&D investment between present and future technology designs

TRL methodology (Héder, 2017). was used to classify 298 government solar PV R&D projects funded by the Korea MOTIE during 2008–2017. The TRL concept was initially developed by the U.S. National Aeronautics and Space Administration (NASA) to increase the predictability of a technology's completion time from real use in aerospace development. TRL provides a useful means for government to utilize R&D strategically to respond to the market. Specifically, R&D policy makers and planners can have a clear vision of where each technology's development level stands with regard to commercialization. In addition, we can understand the government's R&D strategy from the way the budget is allocated among TRL scales.

TRL methodology has been applied in diverse technology fields such as electronics, defense, automobiles, academic, and industrial researchers by many leading countries (Héder, 2017; Philbin, 2013; Schinasi, Rodrigues, & Francis, 1999). In the energy field, the US Department of Energy (DOE) applied the TRL method in 2009 for the first time (Peters, 2017). The Korean government integrated this concept in the request for proposal (RFP) of government R&D grants in 2012 for the more systematic and strategic management of R&D investment and for the prevention of risk due to the immaturity of core technologies (The Korea MSIT & KISTEP, 2018). The Korean TRL relies on the original nine scales found NASA's TRL method.

The definitions are applied to all Korean government funded R&D projects from 2008 to 2017. For those projects funded between 2008 and 2011, prior to the use of the TRL method in Korea, the TRL assessment was done by an expert committee which consisted of two engineering professors of Green School at Korea University and three PhD candidates in the College of Engineering at Korea University. In assessing all PV projects during the study period, the committee adopted the Korean government's official nine scale definition of TRL. The projects were then aggregated into four scales consistent with classification standards of the International Technology Roadmap for Photovoltaic (ITRPV). ITRPV (2018)'s four scale definitions of technology maturity are more convenient for understanding the general state of technology commercialization. Table 2 shows ITRPV's definitions.

Figure 2 demonstrates the changes in PV technology readiness and Korean government R&D strategy. In the early stage of PV technology development, technologies remained at the feasibility stage but then PV in the country achieved rapid technology maturity within a short period. As technology maturity grew, R&D grants started to be disseminated to technologies that were close to commercialization. The Korean government implemented a solar R&D strategy which followed a two-track

TABLE 2 International Technology Roadmap for Photovoltaic's (ITRPV's) parameters of photovoltaic technology maturity

Maturity	Technology readiness level (TRL)	Description
Mass production	TRL 8-9	Industrial solution exists. Cost optimization in mass production being done.
Industrial solution	TRL 6-7	Industrial solution is known. Cost optimized mass production not done.
Interim solution	TRL 4-5	Interim solution is known, but too expensive or not suitable for production.
Feasibility	TRL1-3	Feasibility is known. Industrial solution is not known.

Source: ITRPV, 2018.

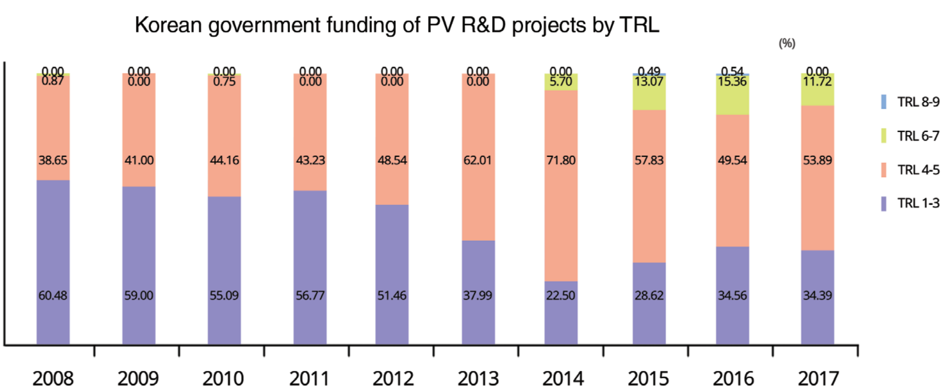

FIGURE 2 Government solar photovoltaic R&D projects investment by technology readiness level (TRL). *Data*: The Korea MOTIE

approach of nurturing commercialization technology to cope with the current global market and at the same time, positioning the country to develop future technology and be a first mover in emerging markets.

This strategy also appears in the budget allocations made between silicon and nonsilicon solar cell R&D. Silicon R&D has mainly concentrated on efficiency improvements in solar cells to strengthen current market competitiveness whereas non-silicon R&D has been an investment for future first mover opportunities.

As shown in Figure 3, their investment proportion has changed over three phases. At the initial stage of the country's market entry (2008–2010), R&D investment put more weight on silicon technology. In the second phase (2011–2012), when global market competition intensified and the country's PV industry started to gain competitiveness, the government moved to include funding for future technology. However, government increased silicon R&D portion again and has kept a balance between silicon and nonsilicon in the third phase. It is consistent with a global market trend that emphasizes increased efficiency of silicon-based solar cells at the same time that pressure on solar cell prices, is for then to decline, mainly arising from mass supply of PV modules from low-cost Chinese manufacturing (Goodrich et al., 2013). Under this circumstance, second generation solar cells have failed to replace the existing silicon-based solar cell market.

4 | IMPACT OF KOREAN GOVERNMENT'S PV R&D INVESTMENT

As discussed above, government R&D investment in PV technology targets export of products and cultivates a PV industry as a source of future manufacturing growth. Global PV market demand is steadily growing as countries face calls to reduce CO_2 emissions (Shiao, 2015). Furthermore, PV industry demonstrated a positive effect on job creation (Sooriyaarachchi, Tsai, El Khatib, Farid, & Mezher, 2015). The Korean government has implemented diverse policies to make the country's PV industry competitive and R&D has been a key pillar in these policies (Jin, Kim, Hwang, Hong, & Lee, 2010; Kim, Oh, Kang, & Kim, 2011; Park et al., 2015).

To evaluates the achievement of Korean PV R&D investment, two indicators were used. As described in Table 3, indicators can map economic impacts of PV R&D, while others can trace technology innovation. The performance of Korean government's PV R&D can be evaluated in both dimensions.

4.1 | Economic effect

A large number of existing literature demonstrates that technology push among industrialization policies usually creates maximum economic effects by increasing export, cost reduction, production, and employment (Akcali & Sismanoglu, 2015; Ehie & Olibe, 2010; García-Manjón & Romero-Merino, 2012; IEA-ETSAP and IRENA, 2013; Jin et al., 2010; Zhang, Ding, & Ke, 2019). This article uses global market share, module price, total sales revenue, and number of employed by industry, as

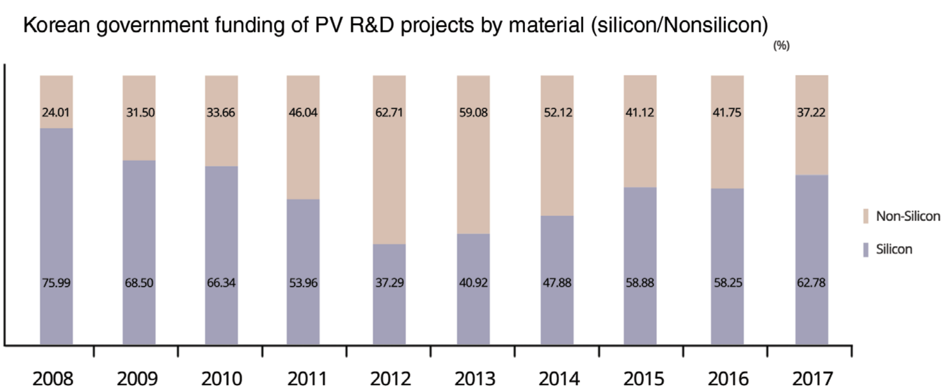

FIGURE 3 Budget allocation between silicon and nonsilicon solar cell. *Data*: The Korea MOTIE

TABLE 3 Indicators for the effectiveness assessment of photovoltaic (PV) R&D strategy

Factors	Indicators
Economic	Global market share, module price, total sales revenue, number of employed by industry
Technological	(Silicon) module efficiency (Nonsilicon) technology level

indicators of export, cost reduction, production, and employment. For the Korean PV R&D policy, economic effects are modest if any. The government significantly cut R&D funding for silicon-based technologies and cannot take credit for Korean silicon PV industry's recent economic growth. The Korean government also pursued a strategy to be a first mover in the nonsilicon-based solar cell market, but this market did not grow fully as expected. The global market share of thin film solar cells based on CdTe and CI(G)S achieved a peak of 17% in 2009 and continued to decrease to a 5% level in 2017 and the market for third generation solar cell is not formed yet (Fraunhofer ISE, 2019; Major, 2018).

In light of China's market dominance, the Korean PV industry focused on silicon technology in order to grow or, at least, maintain a constant market share. Change in market power among PV manufacturers has been significant with the United States and Japanese module producers gradually disappearing from the global top 10 companies by 2017 (2019, The Korea Photovoltaic Industry Association). Korea's market share has stayed around 5–7% with the exception of 2013 when the industry was under restructuring. By contrast, the global market shares of Japan and the United States, which reached 22 and 14% in 2009 respectively, decreased and were at 2 and 1% each in 2017. While China's successful effort to cut cell prices between 2010 and 2012 led to deep and sustained declines in market share for the PV industries of Japan and the United States, Korea's industry was spared this experience, with the exception of the loss of market share in 2012. Even the Korean loss in 2012 proved temporary as industry revenues and employment rebounded and resumed a pattern of steady economic performance after 2012 (Figure 4).

Korea's constant market share was also reflected on the industry's total sales revenue and employment. The global PV market recession and price fall in 2012 had an impact on the country's sales revenue. The revenue dropped in that year but recovered fast to maintain a constant level in recent years. Employment showed a similar trend as sales revenue change, but with a year time lag. For instance, a market shock in 2012 had an effect on employment up until 2013. Again, employment contrasts

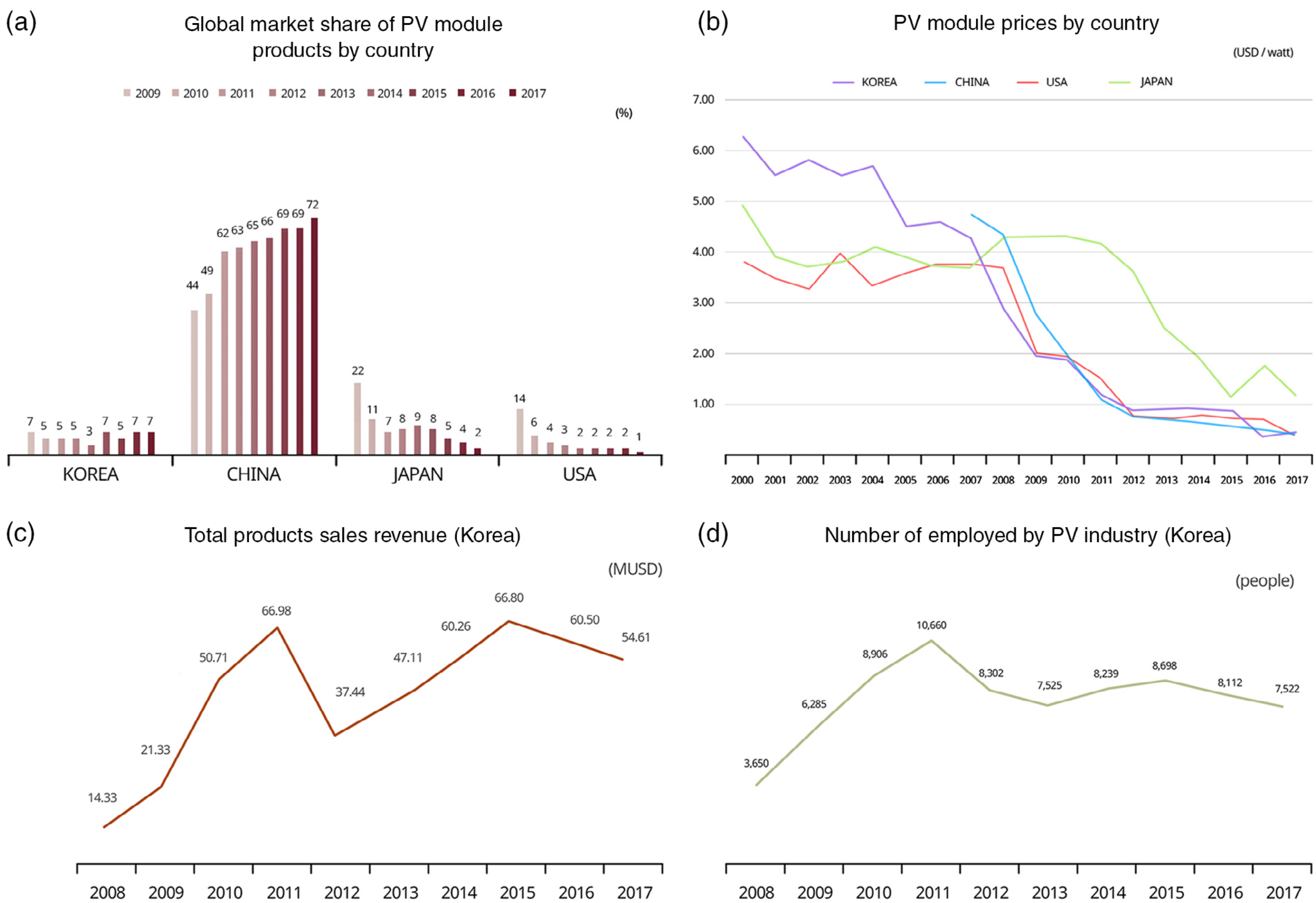

FIGURE 4 Economic performance of the Korea photovoltaic (PV) Industry. *Data*: IEA PVPS (2000–2006, 2007a–2010a, 2007b–2010b, 2011, 2012, 2013a, 2013b, 2013c, 2014a, 2014b, 2015–2018), OECD Monthly Monetary and Financial Statistics (MEI): Exchange rates (USD monthly averages)[9]

to sales revenue with its placid slope when compared to that of sales. This means that employment is less responsive to sales increase. It came from the current automation of PV products production lines (IRENA, 2017).

Prices of PV modules have decreased greatly during the last several decades. Several factors have caused this decline, including R&D, according to researchers of the technology (Kavlak, McNerney, & Trancik, 2018; Taghizadeh-Hesary et al., 2018). Since 2000, Korea's PV industry accomplished a dramatic cut in module prices. Between 2000 and 2017, module prices in Korea dropped by 92.81%, while Japan and the United States recorded declines of 77.09 and 89.73%. China, whose data are available only between 2007 and 2017, realized a 91.54% decline.

The trends displayed by the Korean PV industry's global market share had no clear relation to national R&D policy. As plotted in Figure 4, Korea has managed to carve out a share of the global PV market and remained competitive in its prices of PV markets, rivaling China's prices. This appears mainly to be the consequence of business strategy rather than the R&D policy.

4.2 | Technology advancement effect

It is not easy to estimate the effect of R&D on technology. For this review, module efficiency at mass production (silicon-based technology) and technology level surveys are used to evaluate technological effect. PV module efficiency has continuously improved and has become a key element of market competitiveness. For Korean PV manufactureres to maintain market share amid China supply diminance, product quality expressed by module efficiency is a very important aspect. Figure 5 compares PV module efficiency of commercial and residential projects in California, USA and the average efficiency of Korean domestic module products certified by the Korea Energy Agency for Korean market sales. The domestic PV market in the United States generally and California specifically is larger than the Korean domestic market, making comparisons difficult. Nonetheless, the trend in Korean PV module efficiency improvement is evident. In fact, in the early period of 2010–2013, Korean modules performed slighlty better, while modules installed in California after 2013, especially for commerical applications, were better. Most of these modules were made by Chinese manufacturers. Slower progress in Korean module performance after 2013 coincides with the decline in government PV R&D (Figure 1, panels (a) and (b)), but no definite conclusion can be reached about the relationship between government PV R&D and market competitiveness of Korean manufactuers. There is simply too little data to form a precise model of the relationship.

According to Energysage's 2019 solar panel efficiency rating of PV modules by manufacturer, two Korean makers—LG and Hanwha Qcell—ranked in the top 10 with efficiencies of 21.10 and 19.60%, respectively. While the Korean government's growing PV R&D support during 2008–2012 could have contributed to the industry's subsequent performance improvement, measured by module efficiency. But other factors were also likely to have been important (including investor interest in LG and Hanwha's business strategies). Again, the lack of data makes it impossible at this time to model the relationship.

Performance of Korea's nonsilicon-based solar technology has not been strong. Korea's MOTIE conducted technology level surveys in 2009, 2012, 2014, and 2016 to identify the efficiency of Korea's thin film energy technology. The surveys asked domestic experts in each technology field to score Korea's technology level against a standard of 100 for the world's

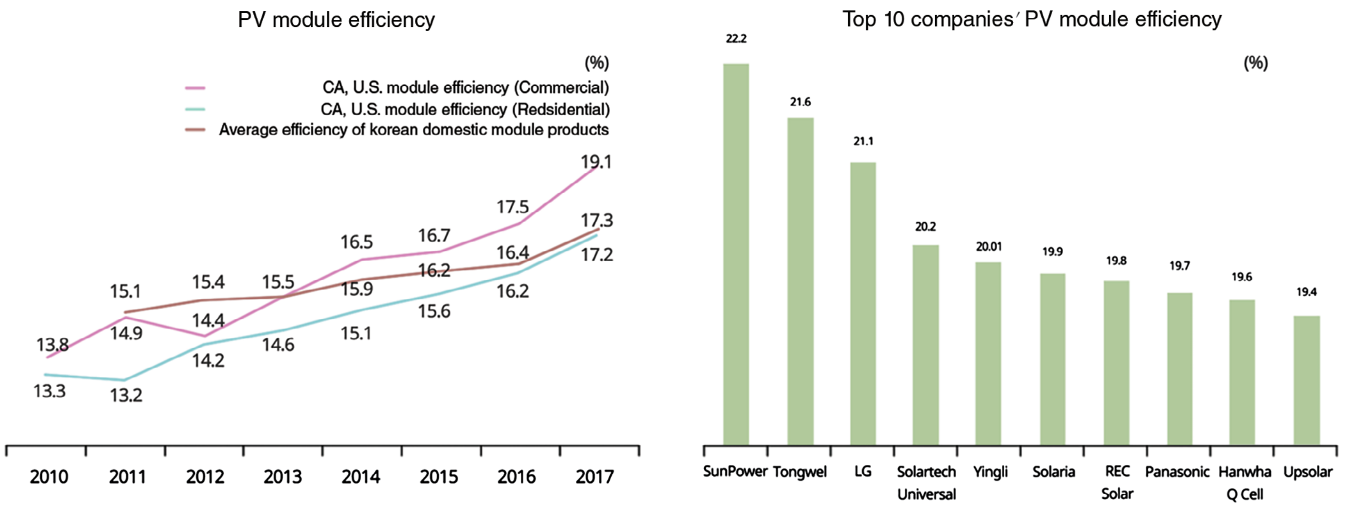

FIGURE 5 Korean photovoltaic (PV) maker's module efficiency achievement. *Data*: Korea Energy Agency, PV Magazine,[10] Energysage[11]

best technology. There are limitations regarding the use of results from those surveys to evaluate technology quality because they depend on experts rather than detailed technology field tests. Nonetheless, these surveys are the only available means of measuring the location of Korean second and third generation PV technologies. Korea's nonsilicon-based thin film technology of CIGS/CdTe earned 80, 89.5, 80, and 80% in 2009, 2012, 2014, and 2016, respectively (A Top Consulting, 2012; GTC, 2014; Korea MOTIE & KETEP, 2009; Korea MOTIE & KETEP, 2016). Organic technology received rankings of 88.6 and 80% in 2012 and 2016 (A Top Consulting, 2012; Korea MOTIE & KETEP, 2016). Dye-sensitized technology received 89 and 90% rankings in 2012 and 2016 (A Top Consulting, 2012; Korea MOTIE & KETEP, 2016). The year 2012 when Korean CIGS/CdTe assumed the highest score, 89.5%, coincides with a period when the Korean government increased R&D investment in thin film and other next-generation technology. Organic technology showed a similar pattern to thin film. This could be evidence that R&D investment facilitated technical improvement to some degree. However, the global market for next-generation technologies has been weak and improvements in efficiency appear not to have been sufficient to expand the market for these technologies. The lack of data also makes it impossible to draw definite conclusions about the role of government R&D in next-generation PV technology performance in Korea.

5 | CONCLUSION

Globally, the PV market has experienced unprecedented changes and challenges. Its market potential has expanded exponentially. Behind this good news for global efforts to diffuse this technology as part of a worldwide search for economical decarbonization of the energy sector, there is heated competition that has led to company bankruptcies, mergers, and acquisitions (Lee, Yoo, Han, Cha, & Jeon, 2017). The market passed through a boom cycle, a recession, and a recovery in only a decade. During the process, PV manufacturers of each country were challenged to identify strategies for profitability in the industry. During this volatile period, Korean PV industry has generated meaningful gains in GDP, employment, and exports. It is partly indebted to government strategies responding flexibly to market changes. The two-track approach of the Korean government may have facilitated progress in silicon-based PV development, while maintaining a measure of competitiveness in the range of nonsilicon PV technologies, although the evidence is inconclusive at this point.

According to an analysis of PV R&D projects funded by DOE[4] under the SunShot Initiative, the U.S. government has invested mainly in compound thin film and nanosolar cells. Japan, which had invested in technology development to support the high efficiency of commercial solar cells, has greatly increased its investment in R&D for next-generation thin film solar cells in the 2010s (Gul, Kotak, & Muneer, 2016; ISPRE, 2009). Despite the market delay for next-generation technologies' commercialization, Korea's R&D focus maintained sizable sustained commitments to nonsilicon technology development. Korea's R&D community continued to press the government to invest R&D fund in nonsilicon-based technologies.

Ever growing competition in the marketplace challenges PV's profitability. The cost of PV power generation reached grid parity in Europe, the United States, and parts of Asia (Denholm, Margolis, Ong, & Billy, 2009; IRENA, 2018), indicating that solar power is a mainstream energy source in some countries and will be in many more countries in the near future. But the ability of PV manufacturers to maintain or increase global market share in an increasingly competitive market is constantly at risk. This challenge will continue as the market for next generation PV technologies heats up.

We conclude that the impact of Korean government's PV R&D strategy on the country's PV industry growth is unclear. Next-generation technology development by Korea is lagging. A significantly higher level of R&D funding may need to be invested in next-generation technologies for Korean industry to be a “first mover.”

ACKNOWLEDGMENT

This work was supported by KU-KIST Graduate School Project, the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (MOTIE) (No. 20188550000450), and Foundation for Renewable Energy and Environment.

CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

YoonHee Ha: Conceptualization; data curation; formal analysis; investigation; methodology; visualization; and writing-original draft. **John Byrne**: Conceptualization; formal analysis; supervision; writing, review, and editing. **HaeSeok Lee**: Conceptualization; data curation; formal analysis; and methodology. **YeJin Lee**: Data curation and visualization. **Donghwan Kim**: Conceptualization; methodology; and supervision.

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ENDNOTES

[1] Retrieved from http://www.law.go.kr/LSW/eng/engLsSc.do?menuId = 2&section=lawNm&query=energy+act&x=0&y=0#liBgcolor6.

[2] Retrieved from http://www.law.go.kr/LSW/eng/engLsSc.do?menuId=2&query=energy%20act#liBgcolor25.

[3] The enterprises who win government's R&D fund are required to contribute a certain proportion toward the research and small and medium businesses' contribution is smaller compared to that of conglomerates.

[4] Retrieved from https://www.energy.gov/eere/solar/photovoltaics-research-and-development.

[5] Retrieved from http://pvinsights.com/.

[6] Retrieved from https://databank.worldbank.org/data/reports.aspx?source=2&series=NY.GDP.MKTP.CD.

[7] Retrieved from https://stats.oecd.org/index.aspx?queryid=169.

[8] Retrieved from https://pv-magazine-usa.com/2018/12/20/higher-module-efficiency-and-inverters-driving-solar-power-cost-declines/.

[9] Retrieved from https://news.energysage.com/what-are-the-most-efficient-solar-panels-on-the-market/.

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How to cite this article: Ha Y-H, Byrne J, Lee H-S, Lee Y-J, Kim D-H. Assessing the impact of R&D policy on PV market development: The case of South Korea. *WIREs Energy Environ*. 2020;9:e366. https://doi.org/10.1002/wene.366