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Has Korean growth become greener? Spatial econometric evidence for energy use and renewable energy

Erik Hille¹ · Bernhard Lambernd¹

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Abstract

Using province-level data for South Korea, we analyze the dynamic relationship between economic growth and several energy parameters. Specifically, we decompose the growth effect into scale, composition, and technique effects, and control for regional spillovers through the use of a dynamic GMM estimator for spatial panel data models. The analyzed period, ranging from 2000 to 2017, allows us to look for changes in the regional growth effects following the implementation of the National Strategy for Green Growth in 2009. Our estimates show that the scale and composition effect tended to increase both per capita final energy use and energy intensity, outweighing reductions through the technique effect. In contrast, when considering renewable energy production, the scale and technique effect increased and the composition effect decreased the corresponding figures. Thereby, the technique effect was the main driver of increases in renewable energy production. Despite the larger, yet comparatively small share of renewables in Korea's energy mix, no considerable change of the growth effects can be observed since 2009. Therefore, to reduce the risks for the economy and achieve the political objectives of the green growth strategy throughout the whole country and in a timely manner, a stronger commitment seems to be required.

Keywords Economic growth · Energy consumption · Renewable energy · Spatial econometrics · Republic of Korea

JEL classification C21 · O44 · Q41 · Q42 · Q56 · R11

1 Introduction

In 2008, South Korea was the 8th largest energy consumer worldwide (BP, 2019) and more than 90% of final energy use came from fossil fuels, which were almost entirely imported (IEA, 2019; KEEI, 2018). As the nation's leading, export-oriented industries, such as

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automobiles, electronics, shipbuilding, steel, and petrochemicals, are capital- and energy-intensive, this implied significant financial and geopolitical risks for the Korean economy as well as increasing pressures to contribute to climate change mitigation.

In order to lower the dependence on fossil fuel imports, create new industrial green growth engines, and reduce greenhouse gas emissions drastically, the Korean government introduced the long-term National Strategy for Green Growth in 2009.¹ In this context, the First Energy Master Plan was launched, targeting a reduction in energy intensity and fostering the use of renewable energies (MOTIE, 2014). Korea's energy transition is dependent on several regional initiatives and the formation of energy technology clusters. For instance, photovoltaic industry clusters emerged in the provinces Jeollanam, Jeollabuk, Chungcheongnam, and Daegu (Cooke, 2011). Wind power industry clusters are located in various regions, including Jeollabuk and Gyeongsangnam province (Berg & Hassink, 2012). Besides increasing the production of renewable energy sources, smart grids shall be implemented to increase the energy efficiency. By connecting small-scale renewable energy generators of individual households, smart grids are expected to accelerate the use of renewables. A smart grid test bed has been installed in Jeju province (Park et al., 2014).²

Given the importance of regional initiatives for the green growth strategy, we use province-level data for South Korea to analyze the dynamic relationship between economic growth and final energy use as well as the production of renewable energy. Specifically, we decompose the regional growth effects and test whether the effects have changed since the implementation of the National Strategy for Green Growth, thereby controlling for spatial spillovers from nearby provinces.

Our research is embedded in the growth-energy use literature, which is, from an environmental economics perspective, part of the vast growth-environment research. In this context, energy is seen as a common input for production that is, if sourced from conventional energy carriers, closely related to a number of critical environmental pollutants, including carbon dioxide emissions. The sub-strand of research has for example been summarized by Ozturk (2010) and Omri (2014). Early seminal work includes Kraft and Kraft (1978), who analyzed the causality between energy consumption and the gross national product. The methodologies applied in subsequent empirical studies range mostly from causality analyses (Benkraiem et al., 2019; Omri, 2014; Sbia et al., 2014), to index decompositions (Ang & Zhang, 2000; Ma, 2014; Voigt et al., 2014), to comparatively fewer multivariate regression analyses (Cole, 2006; Yu, 2012). The results of the numerous studies, covering various countries and time spans, show a great variety of results and do not allow clear conclusions to be drawn about causality (Ozturk, 2010). Studies on Korea have predominantly applied causality approaches and also detected mixed evidence (Baek & Kim, 2013; Glasure & Lee, 1998; Oh & Lee, 2004). An interesting recent exception are Hille and Lambernd (2020), who analyzed the role of technological change for energy intensity changes using a growth decomposition approach.

Our study contributes to the empirical literature in three main ways. First, this is the first study on the growth-energy use nexus on Korea controlling for regional spillovers. As

¹ Before the adoption of a green growth paradigm, Korea had an average to less strict environmental and climate policy regulation stringency compared to other OECD countries. For example, Korea ranked 13th out of 28 OECD countries in the environmental policy stringency index of the OECD (2020) in the period 1995 to 2008. The corresponding statistic for the climate policy stringency measure of Althammer and Hille (2016) is the 18th rank.

² A map of the considered Korean provinces is provided in Fig. 3 in Appendix A.

Korea's energy transition is dependent on regional initiatives, it seems to be necessary to take spatial interactions into account when specifying the determinants of energy use. Both the generation of energy is organized in regional clusters (Cooke, 2011) and the consumption of energy is driven by Korea's approach to form regional economic areas (Park & Koo, 2013). The limited number of prior spatial studies tended to focus on China (Hao & Peng, 2017; Jiang et al., 2018; Yu, 2012).³ Their findings predominantly confirm the importance of spatial spillovers when assessing the growth effects on energy parameters. The focus of our study is on the effects on final energy use and renewable energy production both in per capita terms and per unit of gross regional product (GDP), i.e. as energy intensities. Specifically, we account for spatial spillover from nearby provinces and the agglomeration of the regional energy initiatives by using a dynamic GMM estimator for spatial panel data models.

Second, we decompose the growth effects into scale, composition, and technique effects, complementing the few studies on the nexus that applied a decomposition approach (Cole, 2006; Tsurumi & Managi, 2010). This approach reflects the criticism of the practice to estimate environmental Kuznets curves, which seek to describe a simple relationship between income and pollution that may not fully capture the heterogeneous effects of the various growth drivers (Copeland & Taylor, 2004). We explicitly control for the scale effect that accounts for the impact of increased economic activity. The environmental effect of economic growth- and trade-induced changes in the industrial composition and pattern of production are captured through the composition effect. The technique effect reflects the increased demand for environmental quality due to higher incomes that usually accompany economic growth. In this regard, the technique effect captures various possible forces, such as environmental regulation (Hille & Shahbaz, 2019; Shapiro & Walker, 2018) and technological change (Hille & Lambernd, 2020; Tsurumi & Managi, 2010).

Third, the analyzed period, ranging from 2000 to 2017, allows us to look for changes in the regional growth effects following the launch of the National Strategy for Green Growth. The First Energy Master Plan that is meant to support the objectives of the National Strategy for Green Growth, set clear objectives to reduce Korea's energy intensity by 46% from 2007 until 2030 and to concurrently increase the share of renewables in the primary energy supply from 2.2 to 11% (MOTIE, 2014). Through the analysis of final energy use and renewable energy production, we are able to identify related changes of the growth effects since 2009, and thus provide an indication whether the political initiatives have so far been successful on the regional level.

Our results suggest that the scale and direct composition effect tended to increase both per capita final energy use and energy intensity, whereas the technique effect reduced them. Besides the technique effect, the trade-induced composition effect lowered the energy parameters, suggesting that pollution offshoring has played a significant role in the reduction of the Korean final energy use. Regarding renewable energy production, we find that the scale and, in particular, the technique effect contribute to increasing the corresponding per capita and intensity figures. In contrast, the direct and trade-induced composition effect reduced the production of renewable energy. While our analysis reveals no considerable changes of the growth effects following the implementation of the green growth strategy,

³ The related literature on the broader growth-environment relationship has a less narrow regional focus. Besides China (Wang & Ye, 2017), studies using spatial econometric approaches have also analyzed few developed economies, such as the U.S. and Japan (Burnett et al., 2013; Cole et al., 2013), and cross-country spatial interactions (Maddison, 2006; Rios & Gianmoena, 2018).

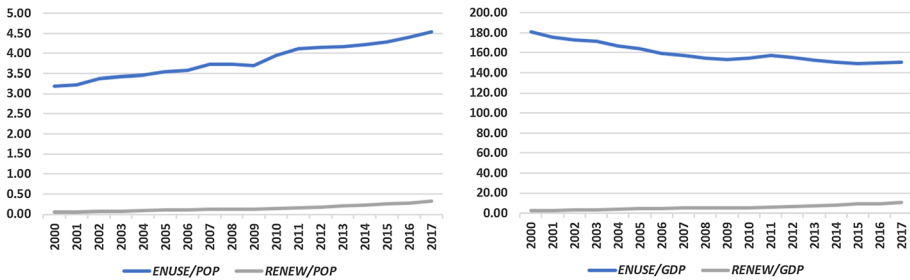


Fig. 1 Development of final energy use and renewable energy production in per capita form and per unit of GDP. *ENUSE/POP* and *RENEW/POP* denote per capita final energy use and renewable energy production in toe. *ENUSE/GDP* and *RENEW/GDP* denote final energy use and renewable energy production per unit of GDP in toe per thousand Won (2010 prices). Self-prepared using KEEI (2018) and KOSIS (2020)

the relevance of spatial interaction effects on the energy parameters becomes evident, especially through spillovers from transportation.

The rest of the paper is organized as follows. In Sect. 2, the national and regional development of the energy parameters is described. Section 3 outlines the empirical model, the panel dataset, and the estimation strategy. In Sect. 4, the regression results are presented and checked for robustness, and Sect. 5 concludes.

2 Development of the energy parameters

Its rapid economic development and focus on capital-intensive industries have made Korea one of the largest energy consumers in the world. In 2017, the industrial sector accounted for approximately 60% of the nation's final energy use, and the transportation and residential sector accounted for approximately 20% each (KEEI, 2018). While Korea's GDP grew by an average 3.8% per year during the period analyzed, i.e. between 2000 and 2017, final energy use increased less dynamically by 2.7% (KEEI, 2018; KOSIS, 2020). This development translated into a slight reduction of the final energy use intensity, which is depicted in Fig. 1, by an average 1.3% per year in the respective period. Yet, the energy intensity is still among the highest of the OECD countries (IEA, 2019). In contrast, per capita final energy use increased by 2.1% annually on average. Conventional energy sources, including imported fossil fuels in particular, have traditionally contributed the main share to the Korean energy mix. As a consequence, the country's energy self-sufficiency was only 17% in 2017 (IEA, 2019). Nonetheless, renewable energies have played an increasingly important role in the energy mix. On average, per capita renewable energy production grew by 12.2% per year between 2000 and 2017, and renewable energy production per unit of GDP grew by 8.7%, respectively.⁴

The main objectives of the national energy policy have been subject to change during the last decades (MOTIE, 2014). Before the 1990's, the predominant objective was

⁴ We focus on renewable energy production, because the Energy Master Plan set a clear target to increase the share of renewable energy in the primary energy supply by 2030. Province-level data on renewable energy consumption is only available from 2002 onwards, but shows a similar development.

to secure energy supply at reasonable price levels. In the early 2000's, policymakers concentrated on the liberalization of the energy market by promoting competition and market-based pricing. In the subsequent years, increased energy security, energy efficiency, and stricter environmental protection were targeted. The First Energy Master Plan from 2008 complemented this policy by setting the goal to achieve low-carbon green growth. The gradual change towards a cleaner and more efficient energy supply is a central element of the Energy Master Plan that targets a reduction of the country's energy intensity and the development of green technologies. Regional initiatives such as the photovoltaic and wind power clusters play a relevant role in achieving these objectives. Based on the aggregate statistics, the targets of the National Strategy for Green Growth and the First Energy Master Plan seem to have partly triggered the right levers. For instance, between 2009 and 2017, renewable energy production increased by an average 13.2% per year, whereas the corresponding figure was only 5.8% for the period 2000–2008.

A main pillar of the Korean economic development has been the organization of the economy in regional industrial complex clusters, with the focus industries changing during the different development phases (KICOX, 2010). In the 1970's, the emergence of several heavy industry and chemical clusters was promoted. In the 1980's, the focus shifted towards technology-intensive industry clusters, and from the 1990's until the launch of the green growth strategy, high-tech IT industry clusters have been Korea's main industrial development pillar. The pattern of production and the importance of particular regional industrial complexes is also reflected in the province-level final energy use statistics, presented in Fig. 2. At the provincial level, Ulsan, Jeollanam, and Chungcheongnam have the highest final energy use both per capita and per GDP. While Ulsan is the largest energy consumer measured in per capita terms in 2017, Jeollanam is the corresponding largest energy consumer measured in per GDP terms. Chungcheongnam shows the highest growth of per capita final energy use since 2000 amounting to an average 5.1% per year. Not surprisingly, the industry structure in these three provinces is dominated by heavy industries. For example, corporations in Ulsan are mainly operating in high energy-consuming industries, such as the automotive, shipbuilding, petrochemical, and secondary cell industry (Ulsan Metropolitan City, 2020). Important industries in Chungcheongnam are heavy industries, such as the automotive, semiconductors, steel, and petrochemical industry (Province of Chungcheongnam, 2019).

In contrast, independent cities, such as Seoul, Gwangju, and Daejeon, have the lowest per capita final energy use and energy intensity. In Seoul, both per capita final energy use and energy intensity even decreased between 2000 and 2017, namely by an average 0.4 and 3.2% per year, respectively. Also larger provinces achieved a reduction of the corresponding figures. For instance, in Gyeongsangbuk and Chungcheongbuk the final energy use intensity decreased by 1.1 and 2.5% per year on average. Although Gyeongsangbuk's economy heavily depends on mining and manufacturing, more than 60% of the employed people recently worked in the service sector (Province of Gyeongsangbuk, 2019). Similarly, with 42.6% the service sector contributes almost as much to Chungcheongbuk's gross regional product as the mining and manufacturing industry with 46.3% (NEAR, 2020).

Figure 2 also shows a strong increase in renewable energy production in nearly all provinces. Of particular note is Jeollanam, which is the jurisdiction with the largest production both per capita and per GDP. Interestingly, in the neighboring province Jeollabuk, per capita renewable energy production strongly grew by an average 20.1% per year between 2000 and 2017 and the corresponding renewable energy production intensity grew by 16.8%. In both provinces, a major share of the Korean photovoltaic and wind power industry is located. However, the strongest increase in renewable energy production both per capita

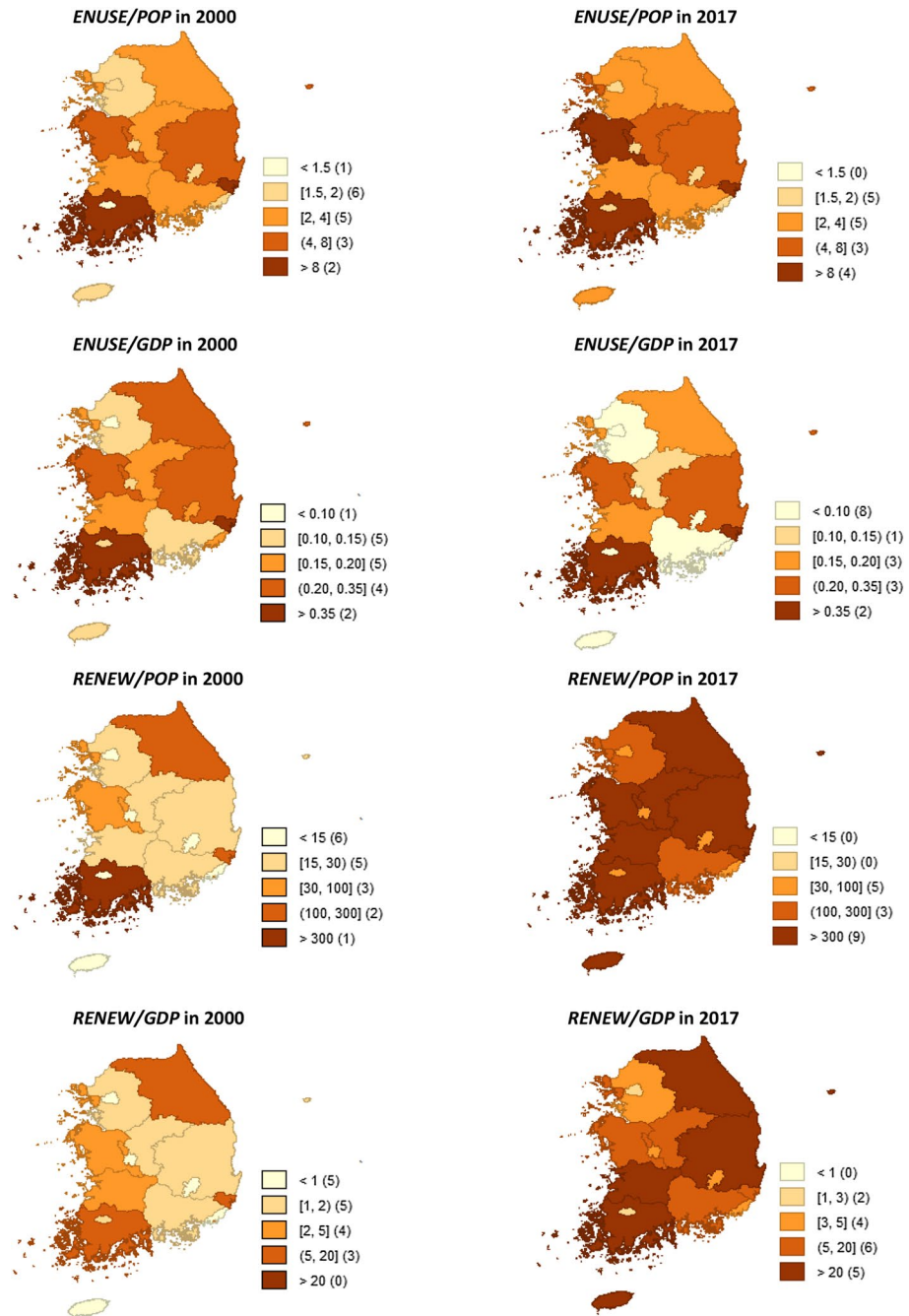


Fig. 2 Energy parameters per capita and per unit of GDP on the provincial level. *ENUSE/POP* and *RENEW/POP* denote per capita final energy use and renewable energy production in toe. *ENUSE/GDP* and *RENEW/GDP* denote final energy use and renewable energy production per unit of GDP in toe per thousand Won (2010 prices). As in the empirical analysis, the figures for Sejong and Chungcheongnam are considered jointly. The numbers in round brackets after the energy parameter ranges are the corresponding province counts. Self-prepared using KEEI (2018) and KOSIS (2020)

and per GDP was achieved in Jeju during the considered period. Guided by national policies, Jeju Island has promoted the expansion of production facilities for wind and photovoltaic (Park et al., 2017).

3 Methodology and data

3.1 Empirical model

To analyze the growth-energy use nexus, we decompose the growth effects into scale, technique, and composition effects. This approach originates from the broader literature on the effects of economic growth and trade on the environment (Antweiler et al., 2001; Cole & Elliot, 2003; Shapiro & Walker, 2018), and has been applied to the energy context in few studies (Cole, 2006; Hille & Lambernd, 2020; Tsurumi & Managi, 2010). Specifically, our model is based on Cole (2006), who applied the approach of Cole and Elliot (2003) to national energy use data. We adjust Cole's (2006) model in four main ways: first, in addition to final energy use per capita and per unit of output, we consider the determinants of the corresponding renewable energy production. Second, we only include a measure of trade openness directly and do not specify individual sources of comparative advantage through interaction effects, because the prime concern of our analysis is not the decomposition of the trade-induced composition effects. Third, instead, to identify regional-level changes since the launch of the green growth strategy, we include a green growth binary as well as corresponding interactions with the terms capturing the scale, technique, and composition effect. Fourth, we account for spatial spillovers from nearby provinces through spatial interaction effects. Equation (1) specifies our empirical model:

$$\begin{aligned} \ln E_{it} = & \alpha_0 + \alpha_1 \ln INC_{it-1} + \alpha_2 \ln INC_{it-1}^2 + \alpha_3 \ln \left(\frac{K}{L} \right)_{it} + \alpha_4 \ln \left(\frac{K}{L} \right)_{it}^2 \\ & + \alpha_5 \left(\ln \left(\frac{K}{L} \right)_{it} * \ln INC_{it-1} \right) + \alpha_6 \ln TRADE OPENNESS_{it} + Z'_{it} \alpha_l \\ & + \alpha_7 GREEN GROWTH + (GREEN GROWTH * V'_i) \alpha_m + \sum_{j=1}^n W_{ij} X'_j \theta \\ & + \mu_i + \mu_t + \varepsilon_{it} \end{aligned} \quad (1)$$

where E denotes either final energy use or the renewable energy production both in per capita form and per unit of GDP, i.e. as energy intensities, in province i and year t . INC is the one period lagged per capita income, whereas K/L is the capital-labor ratio. Additional squared terms and cross products of both variables are included to allow for nonlinear effects and dependencies between the regressors (Cole & Elliot, 2003). Following prior research, $TRADE OPENNESS$ is measuring using trade intensity, i.e. the sum of imports and exports relative to the GDP (Chintrakarn & Millimet, 2006; Hille & Möbius, 2019a; Pham et al., 2020).

Per capita income INC , the capital-labor ratio K/L , and $TRADE OPENNESS$ capture the decomposed growth and trade effects. While INC represents the joint scale and technique effect, when the energy parameters are considered in per capita form, INC measures the technique effect only, when energy intensities are considered as the dependent variable. On the one hand, the scale effect, which reflects increased economic activity, is expected to, ceteris paribus, increase final energy use. This expectation may also apply to renewable

energy production, as part of the increased energy demand is likely to be met by renewables. However, higher prices in the past and limited availability of renewable energy could counteract this positive effect. On the other hand, a higher income, that tends to accompany economic growth, may be associated with an increased demand for environmental quality and thus a lower demand for fossil fuels. Accordingly, the technique effect is expected to lower final energy use, because fossil fuels have contributed the largest share to the Korean energy mix, and foster renewable energy production. *K/L* captures the composition effect. Depending on the change in the pattern of production, the composition effect may either increase or reduce pollution. For instance, a further shift towards capital-intensive industries is expected to increase final energy use and, similar to the scale effect, either increase or decrease the relative production of renewable energy. Moreover, the aggregate, trade-induced composition effect is captured by the term *TRADE OPENNESS*. The effect of trade liberalization on energy use depends on the sources of comparative advantage. Important opposing sources include the country's factor endowments and environmental regulation (Antweiler et al., 2001; Cole, 2006; Cole & Elliot, 2003). In the presence of trade liberalization, the factor endowment hypothesis suggests that capital-abundant countries, like Korea, will further specialize in the production of capital-intensive products, increasing the demand for energy. In contrast, stricter environmental regulation, which the Korean green growth strategy partly entails, may foster clean production and lead to offshoring of pollution-intensive production. Hence, when the latter effect dominates, the domestic demand for energy decreases, and countries with weaker regulation may become pollution havens.

We control for three additional covariates through vector *Z*. First, the number of registered motor vehicles are seen as a main driver of the Korean usage of petroleum (Kim et al., 2011), which has been the main energy source in the energy mix. The number of registered motor vehicles is thus expected to increase energy use. Second, environmental regulation-induced innovation activity tends to reduce pollution, and hence may reduce final energy use that is dominated by conventional energy sources in Korea, and foster renewable energy production (Herrerias et al., 2016; Hille & Lambernd, 2020; Shahbaz et al., 2020). Following prior research in the field, we measure innovation activity rather broadly using the number of patent applications in the main estimations and R&D expenditures in the robustness checks.⁵ Third, a related sub-strand of literature has estimated the effect of FDI inflows on environmental pollution and energy use (Doytch & Narayan, 2016; Lee, 2013; Nasir et al., 2019). Similar to trade liberalization, the expected effect is ambiguous because of opposing hypotheses, such as the pollution halo and the pollution haven hypothesis. Nonetheless, given that the green growth strategy signals a commitment towards clean development, foreign investors that are interested to contribute to this path, may have been attracted.

GREEN GROWTH represents a binary variable that is 1 since the launch of the National Strategy for Green Growth in 2009, and 0 in the period beforehand. We include the binary

⁵ Certainly, our broad measures also include innovations with a wider focus than environmental protection or energy efficiency. Nonetheless, these innovations can influence energy use and renewable energy, for instance through more efficient production processes and the usage of new materials (Hille & Lambernd, 2020). Measures with a more narrow scope, such as environmental innovation (Lee & Min, 2015; Long et al., 2017), energy innovation (Alvarez-Herranz et al., 2017; Balsalobre-Lorente et al., 2018), or renewable energy innovation (Bai et al., 2020; Hille et al., 2020) have also been applied in the literature, but are not used because of data availability in KOSIS (2020). The narrow measures are expected to have a stronger average effect on the considered energy parameters but may omit effects of innovation that are not framed directly to clean the environment.

variable both directly and through an interaction effect with vector V , which contains the linear and squared terms of per capita income INC and of the capital-labor ratio K/L . The direct coefficients of the binary variable indicate whether, after controlling for the specified covariates, final energy use and renewable energy production have altered in general since 2009. The coefficients of the interaction terms capture changes in the scale, technique, and composition effects, and thus provide evidence whether the decomposed regional growth effects have become greener following the change in the national growth paradigm.

To account for spatial spillover on the energy parameters from nearby provinces, we include so-called exogenous spatial interaction effects WX . While W represents the spatial weight matrix that specifies the dependence structure between jurisdictions, X is a vector of all previously determined explanatory variables that includes observations for nearby provinces j . The selection of the spatial econometric model as well as the spatial weight matrix are both specified and motivated in the next Sect. 3.2. Lastly, we control for time and province fixed effects μ_t and μ_i , and ε denotes the error term.

3.2 Spatial model selection and estimator

To avoid biases in the estimated parameters, we control for spatial interaction effects among the independent variables through the WX term. In spatial econometrics, the model selection, definition of the spatial weight matrix, and choice of the estimator are of high importance.

An overview of the spatial econometric models that have been considered in the recent spatial econometrics literature is, for example, provided in Halleck Vega and Elhorst (2015). The different spatial econometric models account for varying spatial effects among the dependent variable, the independent variables, and/or the error term by including interactions of the weight matrix W and the respective term. To explore possible spatial correlations in our data, we begin our testing procedure with Moran's I tests on the dependent and explanatory variables. The results in Table 4 in Appendix A suggest that spatial autocorrelation exists in general for different weight matrices, and hence it is important to control for spatial spillovers. In order to determine the most suitable spatial econometric model, recent model selection strategies start the selection process by considering models with exogenous spatial interaction effects WX as point of departure (Halleck Vega & Elhorst, 2015; LeSage, 2014). Specifically, the approaches focus on the spatial lag of X (SLX) model, the spatial Durbin model (SDM), and the spatial Durbin error model (SDEM).⁶ The reason is that these models are more flexible, as they do not restrict the size of spatial interactions in advance. We follow these recent approaches and determine Bayesian posterior model probabilities (LeSage, 2014), which show that in our particular case the inclusion of exogenous interaction effects WX only, i.e. the SLX model, is the best choice. The choice of an SLX model is also largely confirmed by the often applied past model selection approaches of LeSage and Pace (2009) and Elhorst (2010), which are based on a series of LR tests or a combination of LM and LR tests. Given the limited space and large number of model selection tests performed, detailed test statistics are available upon request.⁷

⁶ While the SLX model includes exogenous interaction effects WX only, the spatial Durbin model and the spatial Durbin error model in addition include spatial interaction effects among the dependent variable and the error term, respectively.

⁷ Examples of robust LM test statistics are shown in Table 4. The results suggest that spatial interaction effects among the error terms are partly relevant for our analysis, i.e. when the 50 km distance matrix is

A key component of spatial econometric models is the spatial weight matrix. Two general types of weight matrices have commonly been used in the few spatial studies analyzing growth effects on energy use. These are contiguity matrices based on boundaries between jurisdictions (Hao & Peng, 2017; Jiang et al., 2018) and distance matrices based on geographical distances between capitals (Hao et al., 2016; Yu, 2012). The selection of the spatial weight matrix generally depends on the context. That is, either the choice is based on the specific research problem and theoretical setting or, if this is absent, the matrix needs to be determined through experience and goodness of fit criteria, because the most suitable functional form to specify the connectivity between jurisdictions is often not obvious (Elhorst, 2010; Hao & Peng, 2017). In this study, we mostly apply distance matrices that consider spatial interactions between two provinces when the geographic distance between their capitals lies within a certain threshold. In this case, the corresponding element of the spatial weight matrix is 1, and 0 otherwise. While the geographic distance between provincial capitals can reflect economic distance as well, because the capitals are often the province's economic center and transportation hub (Yu, 2012), a distance matrix also accommodates the specific administrative characteristics of the Republic of Korea. Specifically, Korea has a relatively large number of autonomous cities among the province-level divisions, that are in parts geographically close to other divisions, but with which they do not share a common border. For instance, a first-order contiguity matrix would omit spatial interactions between the two largest cities of the Seoul metropolitan region, i.e. Seoul and Incheon. In the main estimations, we set the threshold distance to 50 km. To check the sensitivity of our results to changes in the spatial weight matrix, we apply alternative threshold distances as well as a contiguity matrix in the robustness checks Sect. 4.3.

We estimate our model, summarized in Eq. (1), using difference GMM (Arellano & Bond, 1991; Holtz-Eakin et al., 1988) for spatial panel data models. In contrast to frequently applied estimation techniques, such as maximum likelihood and quasi-maximum likelihood (Hao & Peng, 2017; Hao et al., 2016; Yu, 2012), GMM and instrumental variable estimators allow a straightforward application in situations where the spatial econometric model includes one or more potentially endogenous explanatory variables other than the spatially dependent variable (Elhorst, 2010). Prior non-spatial econometric studies on the trade, growth, and environment relationship have often considered income and measures of trade liberalization as endogenous (Chintrakarn & Millimet, 2006; Hille & Shahbaz, 2019; Managi et al., 2009). While this has not been the case in spatial econometric studies on the growth effects on energy use, in our analysis, we accordingly treat income and trade openness as potentially endogenous. The lagged levels of these variables are used as instruments in the transformed equation (Arellano & Bond, 1991; Holtz-Eakin et al., 1988).

Footnote 7 (continued)

used in particular, while interactions among the dependent variables are not. The former result may stem from the omitted WX term that is part of the error term and cannot be directly tested for using LM tests.

3.3 Data

We analyze the growth effects on energy data in 16 Korean provinces and self-governing cities⁸ for the years 2000–2017,⁹ and used various sources to compile the dataset. Firstly, we retrieved the final energy use and renewable energy production data from the Korean Yearbook of Regional Energy Statistics (KEEI, 2018). Secondly, the raw data for most explanatory variables was taken from the Korean Statistical Information Service (KOSIS, 2020). Specifically, this includes information on the gross regional product, population size, trade, motor vehicle registrations, innovation, and deflators, as well as the necessary data to estimate province-level capital-labor ratios. Given that province-level capital stock data is not available, we estimate this parameter following the approaches in prior analyses on Korea (Hille & Lambernd, 2020; Hille et al., 2019). In the base year, these studies distribute the national capital stock among provinces by combining information on sector-specific country-level capital stocks for various asset classes with the provinces' share of value added for each sector. For the subsequent years, province-specific capital stocks are determined with the help of the perpetual inventory method and province-specific data on fixed capital formation and depreciation. Thirdly, data on FDI inflow, which is not publicly available, was received from the Korean Trade-Investment Promotion Agency (KOTRA, 2017). Lastly, for the distance weight matrices, we determined distances between the provincial capitals using geographic coordinates from Google Maps (2020). Table 5 in Appendix A provides an overview of the final variables, their units of measurement, and the regular descriptive statistics.

4 Results and discussion

4.1 Results for final energy use

Tables 1 and 2 report the spatial econometric results for per capita final energy use and final energy use intensity, respectively. We estimate four specifications in each table. That is, in our first estimation in columns (1) and (5), we control for the terms capturing the scale, technique, composition, and trade effects. In columns (2) and (6), we include the three additional covariates, i.e. registered motor vehicles *CARS*, patent applications *PATENTS*, and FDI inflows *FDI*, and refer to these models as our base specification. To test for changes related to the launch of the green growth strategy, the green growth binary is added in columns (3) and (7), and the corresponding interaction effects with the decomposed growth effect terms are added in columns (4) and (8). For each column, both direct effects on province's energy use related to changes in the explanatory variables X in the

⁸ Until 2012, Korea consisted of 16 province-level divisions, i.e. the special city Seoul, six metropolitan cities, eight provinces, and the special autonomous province Jeju. The special autonomous city Sejong was only created during the period analyzed, mainly by amalgamating townships from Chungcheongnam province. Therefore, we consider the figures from Sejong and Chungcheongnam jointly from 2012 onwards.

⁹ For consistency reasons, we rely on the same sample period for our explanatory variables in all estimations, namely the years 2000 to 2016 for all variables in contemporaneous terms. For per capita income, which is lagged by one year, this period is 1999 to 2015. As we analyze the explained variables also as a moving average as an alternative lag structure, the sample period for our explained variables is from 2000 to 2016 in the main estimations and ranges until 2017 for the respective robustness tests. Our findings are robust if data until 2017 is also considered in the main estimations.

Table 1 Regression results for per capita final energy use

	(1)		(2)		(3)		(4)	
	X^a	WX ^a	X	WX	X	WX	X	WX
$\ln INC_{t-1}$	-21.14*** (6.780)	2.345 (8.109)	-22.95*** (6.432)	1.072 (6.696)	-26.49*** (6.230)	-2.571 (6.629)	-23.96*** (6.002)	0.522 (7.404)
$\ln INC_{t-1}^2$	1.418*** (0.460)	0.385 (0.632)	1.539*** (0.426)	0.369 (0.544)	1.798*** (0.380)	0.660 (0.515)	1.620*** (0.406)	0.201 (0.455)
$\ln (K/L)$	11.66** (4.497)	0.930 (6.323)	11.59*** (4.330)	1.676 (5.106)	13.40*** (3.998)	5.294 (4.545)	13.10*** (3.982)	1.935 (6.157)
$\ln (K/L)^2$	0.279 (0.243)	1.826*** (0.463)	0.432** (0.183)	1.465*** (0.526)	0.599*** (0.138)	1.565** (0.621)	0.392 (0.418)	0.624 (0.497)
$\ln (K/L) \times \ln INC_{t-1}$	-1.404** (0.556)	-1.957* (1.007)	-1.550*** (0.487)	-1.647* (0.940)	-1.896*** (0.345)	-2.084** (0.942)	-1.674*** (0.612)	-0.833 (0.509)
$\ln TRADE\ OPENNESS$	-0.095*** (0.027)	-0.016 (0.039)	-0.049 (0.033)	-0.051 (0.041)	-0.056* (0.033)	-0.046 (0.038)	-0.060* (0.036)	-0.020 (0.041)
$\ln CARS$			0.234*** (0.058)	-0.211*** (0.056)	0.243*** (0.046)	-0.215*** (0.055)	0.223*** (0.044)	-0.162*** (0.047)
$\ln PATENTS$			-0.054* (0.027)	0.025 (0.036)	-0.082*** (0.029)	-0.021 (0.039)	-0.048* (0.025)	-0.009 (0.030)
$\ln FDI$			-0.003 (0.004)	-0.003 (0.003)	-0.003 (0.003)	-0.003 (0.003)	-0.003 (0.003)	-0.002 (0.003)
GREEN GROWTH			0.070** (0.025)		0.070** (0.025)	-0.066*** (0.022)	1.728 (9.714)	0.379 (23.95)
$\ln INC_{t-1} \times GG$							-0.109 (2.864)	2.758 (5.449)
$\ln INC_{t-1}^2 \times GG$							0.004 (0.140)	-0.149 (0.275)

Table 1 (continued)

	(1)		(2)		(3)		(4)	
	X^a	WX ^a	X	WX	X	WX	X	WX
$\ln(ENUSE/POP)$								
$\ln(K/L) \times GG$							-0.460	-5.347
$\ln(K/L)^2 \times GG$							(5.310)	(5.624)
Constant	60.53 (41.97)		74.63** (37.08)		97.20*** (37.38)		0.052	0.544
Observations	272		272		272		(0.522)	(0.561)
Log-likelihood	360.78		379.41		383.91		77.77**	
Wald test	785.11***		5004***		3274***		(38.70)	
F-statistic	65.43***		312.77***		218.28***		272	
Elasticities							395.65	
Scale & technique	0.484		0.347		0.273		3186***	
Composition	0.082		0.301		0.590		177.00***	
Trade	-0.111		-0.100		-0.101		0.405	
							0.198	
							-0.080	

Robust standard errors are in parentheses; difference GMM is used to estimate the specifications

^aX refers to the non-spatially weighted explanatory variables and WX to the spatially weighted explanatory variables

* $p < 0.10$

** $p < 0.05$

*** $p < 0.01$

Table 2 Regression results for final energy use intensity

	(5)		(6)		(7)		(8)	
	X^a	WX ^a	X	WX	X	WX	X	WX
$\ln INC_{t-1}$	-22.02*** (6.575)	5.423 (8.500)	-22.77*** (6.060)	4.033 (7.239)	-26.14*** (5.695)	0.968 (7.025)	-24.00*** (5.456)	1.968 (7.606)
$\ln INC_{t-1}^2$	1.399*** (0.446)	0.141 (0.686)	1.457*** (0.410)	0.176 (0.602)	1.701*** (0.350)	0.442 (0.562)	1.542*** (0.372)	0.250 (0.491)
$\ln (K/L)$	11.05** (4.261)	-1.419 (6.909)	10.30** (4.167)	-0.287 (5.617)	12.12*** (3.803)	3.088 (5.028)	11.93*** (3.719)	-1.033 (6.619)
$\ln (K/L)^2$	0.250 (0.251)	1.683*** (0.515)	0.402** (0.200)	1.435** (0.593)	0.536*** (0.147)	1.564** (0.627)	0.316 (0.385)	1.361** (0.558)
$\ln (K/L) \times \ln INC_{t-1}$	-1.323** (0.538)	-1.588 (1.126)	-1.403*** (0.491)	-1.429 (1.046)	-1.720*** (0.320)	-1.874* (0.986)	-1.495*** (0.554)	-1.281* (0.689)
$\ln TRADE\ OPENNESS$	-0.090*** (0.029)	0.0004 (0.049)	-0.046 (0.030)	-0.036 (0.045)	-0.053* (0.030)	-0.034 (0.040)	-0.064* (0.038)	-0.018 (0.048)
$\ln CARS$			0.148** (0.058)	-0.345*** (0.057)	0.149*** (0.047)	-0.349*** (0.053)	0.142*** (0.046)	-0.300*** (0.048)
$\ln PATENTS$			-0.047* (0.024)	0.012 (0.037)	-0.073*** (0.027)	-0.025 (0.038)	-0.043 (0.028)	-0.018 (0.030)
$\ln FDI$			-0.005 (0.004)	-0.002 (0.003)	-0.004 (0.003)	-0.001 (0.003)	-0.004 (0.003)	-0.001 (0.003)
GREEN GROWTH					0.070*** (0.022)	-0.061*** (0.021)	5.341 (8.615)	-5.502 (22.25)
$\ln INC_{t-1} \times GG$							-1.365 (2.815)	3.161 (4.742)
$\ln INC_{t-1}^2 \times GG$							0.064 (0.137)	-0.166 (0.241)

Table 2 (continued)

	(5)		(6)		(7)		(8)	
	X^a	WX ^a	X	WX	X	WX	X	WX
$\ln(ENUSE/GDP)$								
$\ln(K/L) \times GG$							0.645	- 3.761
$\ln(K/L)^2 \times GG$							(5.491)	(5.881)
Constant	51.45 (42.91)		61.86 (37.83)		81.23** (35.82)		- 0.051	0.369 (0.588)
Observations	272		272		272		272	
Log-likelihood	352.37		373.19		377.24		382.69	
Wald test	345.51***		245.26***		12,864***		14,583***	
F-statistic	28.79***		15.33***		714.65***		810.19***	
<i>Elasticities</i>								
Technique	- 0.334		- 0.201		- 0.226		- 0.131	
Composition	- 0.089		0.115		0.303		- 0.009	
Trade	- 0.090		- 0.083		- 0.090		- 0.083	

Robust standard errors are in parentheses; difference GMM is used to estimate the specifications

^aX refers to the non-spatially weighted explanatory variables and WX to the spatially weighted explanatory variables

* $p < 0.10$

** $p < 0.05$

*** $p < 0.01$

province itself (Sub-columns X) and cumulative indirect spatial effects related to changes in X in nearby provinces are displayed (Sub-columns WX).

In Table 1, we find significantly negative direct coefficients for INC_{t-1} and positive ones for INC_{t-1}^2 in all specifications, implying the existence of a U-shaped relationship between income and energy use. Similar to Cole (2006), our results provide evidence for a strong technique effect that reduces the scale effect in particular at medium income levels. The composition effect, measured by the capital-labor terms K/L and K/L^2 , is found to increase per capita final energy use, suggesting that a shift towards capital-intensive industries undermines efforts to reduce per capita energy use. This is in line with prior decomposition analyses that estimated direct growth effects only (Cole, 2006; Tsurumi & Managi, 2010). We also detect significant indirect spatial effects for K/L^2 . Hence, rises in nearby provinces' capital-labor ratio tend to increase domestic energy use in particular when nearby provinces have a relatively high capital intensity. Except for the base specification, increases in the trade intensity of provinces are found to reduce per capita energy use directly. This suggests that pollution offshoring motives mainly drive the trade effect. In the process of trade liberalization, Korean firms appear to have outsourced parts of their pollution-intensive production to countries with lower environmental regulations (Chung, 2014).

The coefficient estimates of the control variables are mainly in line with our expectations. While the number of registered motor vehicles has a positive direct effect on per capita energy use, negative spatial spillovers are estimated. The latter effect may be explained by the fuel consumption of vehicles by people commuting or travelling between nearby provinces. An increase in the number of patent applications tends to reduce per capita final energy use directly, confirming the findings of prior research on the effects of domestic innovation activity on energy use and intensity (Herrerias et al., 2016; Shahbaz et al., 2020). In our main estimations, the effect of FDI inflows on energy use is insignificant, which may be attributed to the relatively low value of FDI inflows compared to the size of the Korean economy (KOSIS, 2020; KOTRA, 2017).

With regard to regional-level changes since the launch of the green growth strategy, the results are mixed. While mutually counterbalancing positive direct effects and negative indirect spatial effects of similar magnitudes are estimated for the green growth binary in column (3), the corresponding coefficients become insignificant once changes in the growth effects since 2009 are controlled for in column (4). Hence, after taking the effects of the other determinants into account, we detect no convincing evidence for a general reduction of per capita final energy use since 2009. Similarly, a significant change of the decomposed growth effects cannot yet be observed following the paradigm shift in the industrial and environmental policy. In other words, the results for the added interaction terms in column (4) indicate that the growth effect elasticities have not become greener.

To interpret the average magnitude of the total growth and trade effects, we calculate elasticities based on the mean values of the variables and add the direct with the indirect spatial effects. For an average Korean province, the joint scale and technique effect increases per capita energy use, suggesting that the scale effect dominates the technique effect. Overall, the joint scale and technique effect tends to be the strongest driver of per capita energy use in an average province. Besides the scale effect, a shift towards more capital-intensive industries, as captured by the composition effect, drives per capita energy use increases. While these elasticity estimates are in line with the findings of Cole (2006), those of the trade effect are the opposite. That is, the total trade effect tends to lower per capita energy use. Similar evidence was found for example in Sbia et al. (2014) for aggregate energy demand. Even though we detect relatively small trade effects, the results again highlight the importance of pollution offshoring motives for Korean enterprises.

The results in Table 2 for final energy use intensity are very similar to those for per capita final energy use. The main difference is that the per capita income terms INC and INC^2 capture the technique effect only, because the regressand is an intensity. We again find direct coefficient estimates of per capita income that suggest a U-shaped relationship as well as a strong reduction in energy intensity through the technique effect at medium income levels. The increasing effect of INC^2 on energy intensity can be interpreted as a rebound effect at higher income levels. Following the argumentation of prior analyses, energy efficiency gains are often offset by rebound or backfire effects (Hanley et al., 2009; Turner & Hanley, 2011). Nonetheless, according to the elasticity estimates, the total technique effect is the main driver of energy intensity reductions of an average Korean province. With regard to the composition effect, increases in the capital-labor ratio are found to increase the final energy use intensity both directly and indirectly through spatial interactions between provinces. Hence, in general, a further shift towards capital-intensive industries appears to be related to higher energy intensity. Despite of this, the composition effect elasticities of an average Korean province are less pronounced than in Table 1, and in columns (5) and (8) even negative but close to zero. The trade effect tends to reduce the final energy use intensity, providing confirmatory evidence for pollution offshoring tendencies in the Korean economy, detected in studies such as Chung (2014) and Hille and Lambernd (2020). Similarly, the impact of the control variables on energy intensity are largely in line with the results for per capita energy use. That is, we estimate significant direct as well as indirect spatial effects of registered motor vehicles, and increased innovation activity, captured by the number of patent applications, tends to reduce energy intensity. Likewise, the coefficients of both the direct green growth binaries and the corresponding interaction terms with the decomposed growth effects do not indicate clear improvements in the final energy use intensity since 2009 due to determinants other than those already disclosed. The influence of the green growth strategy on the energy use pattern of regional economic growth appears to be rather limited so far.

4.2 Results for renewable energy production

Table 3 displays the estimates for renewable energy production both in per capita form in columns (9) and (10) and per unit of GDP in columns (11) and (12). We concentrate on the models that correspond to the second and third specification in Sect. 4.1. Consequently, in the base specification in columns (9) and (11), we control for the growth and trade effects as well as the three additional control variables, and in columns (10) and (12), we add the green growth binary.¹⁰

With regard to income, we estimate negative direct effects for the linear term INC and positive ones for the squared term INC^2 across all columns, translating into a U-shaped relationship with turning points at lower income levels. The shape suggests that both the scale and the technique effect foster the adoption of renewable energies at higher income levels. At lower income levels, conventional energy carriers seem to be preferred, indicating that the focus has been on a comparatively cheap and stable energy production. Nonetheless, for an average province, the scale and technique effect have a positive effect on renewable energy production, both in per capita form and per unit of GDP. As expected,

¹⁰ Table 3 only shows the results for these two specifications as space is limited and the additional estimations do not provide opposing findings. Further results are available upon request.

Table 3 Regression results for renewable energy production

	ln (RENEW/POP)			ln (RENEW/GDP)		
	(9)	(10)	(11)	(12)	(13)	(14)
	X ^a	X	X	X	X	X
	WX ^a	WX	WX	WX	WX	WX
ln INC_{t-1}	-105.8** (44.08)	-111.1*** (39.33)	-105.6** (43.42)	-110.8*** (38.57)	39.96 (72.65)	41.13 (80.05)
ln INC_{t-1}^2	8.010*** (3.059)	8.360*** (2.650)	7.927*** (3.025)	8.263*** (2.611)	-3.945 (6.792)	-3.706 (7.096)
ln (K/L)	68.59** (32.37)	72.94** (29.46)	67.30** (32.17)	71.67** (29.23)	-31.46 (76.07)	-27.31 (78.52)
ln (K/L) ²	3.547* (1.860)	3.431* (1.823)	3.517* (1.821)	3.369* (1.783)	-4.616 (6.858)	-3.972 (6.466)
ln (K/L) × ln INC_{t-1}	-10.48*** (3.876)	-10.82*** (3.258)	-10.33*** (3.860)	-10.65*** (3.242)	7.795 (13.67)	6.692 (13.43)
ln TRADE OPENNESS	-0.132 (0.283)	-0.142 (0.290)	-0.130 (0.282)	-0.138 (0.289)	-0.472** (0.221)	-0.507** (0.246)
ln CARS	2.320*** (0.534)	2.219*** (0.480)	2.234*** (0.534)	2.125*** (0.482)	-0.972*** (0.335)	-0.989*** (0.325)
ln PATENTS	0.104 (0.214)	0.065 (0.246)	0.112 (0.219)	0.074 (0.252)	0.278* (0.164)	0.329 (0.217)
ln FDI	0.0003 (0.013)	0.001 (0.013)	-0.001 (0.013)	-0.001 (0.013)	-0.019 (0.013)	-0.016 (0.014)
GREEN GROWTH		0.215 (0.160)	0.205 (0.159)	0.220 (0.159)		
Constant	217.3 (244.0)	219.2 (257.7)	204.5 (239.6)	203.2 (253.5)		

Table 3 (continued)

	ln (RENEW/POP)			ln (RENEW/GDP)		
(9)	(10)	(11)	(12)			
X^a	X	WX	WX			
Observations	272	272	272			
Log-likelihood	- 124.01	- 121.70	- 124.24			
Wald test	260.16***	3037***	75,544***			
F-statistic	17.34***	168.77***	4722***			
<i>Elasticities</i>						
Scale & technique	2.514	2.936	1.963			
Technique			2.338			
Composition	- 0.749	- 1.416	- 1.737			
Trade	- 0.619	- 0.661	- 0.645			

Robust standard errors are in parentheses; difference GMM is used to estimate the specifications

^a X refers to the non-spatially weighted explanatory variables and WX to the spatially weighted explanatory variables

* $p < 0.10$

** $p < 0.05$

*** $p < 0.01$

through increased economic activity, the scale effect appears to raise energy demand, and parts of the higher energy demand are covered by renewable energy. The income-induced technique effect may have fostered renewable energy production through various possible forces, such as stricter environmental regulation and green technological change. When comparing the magnitudes of the joint scale and technique effect with those of the technique effect, one may deduct that the technique effects are larger than the scale effects. In other words, the technique effect has been the main driver of increases in renewable energy production. This finding complements recent corresponding evidence of Hille and Lambernd (2020) on the importance of the technique effect for changes in the renewable energy consumption intensity. Interestingly, the magnitude of the scale and technique effects is larger than the corresponding values for final energy use, suggesting that increased renewable energy production can potentially be achieved more easily through increased income and accompanied commitment. The same picture emerges for the magnitudes of the direct composition effect as well as the trade-induced composition effect, discussed in the following.

Changes in the capital-labor ratio are estimated to affect renewable energy production directly, whereas no significant spatial spillover effects are found, which is different to the results for final energy use in Sect. 4.1. On average, the total composition effect elasticities are negative, suggesting that a shift towards more capital-intensive and thus energy-intensive production does not entail higher renewable energy production. Capital-intensive industries seem to have covered their additional energy demand with conventional energy carriers. A possible explanation could be that these industries tend to face strong international competition, resulting in higher cost pressures. This contrasts with the lack of cost parity of renewables until recently and their limited availability.

The estimated coefficients of trade openness are all negative, but only the indirect spatial effects are significant. Overall, the trade effect reduces renewable energy production in per capita form and per unit of GDP for an average province. The intuition of the negative effects is related to prior explanations. On the one hand, pollution offshoring has reduced final energy use, and as renewable energy is one of the energy sources in the energy mix, it is also less demanded. On the other hand, capital-intensive exporting industries may have demanded less renewable energy, because of cost pressures related to international competitiveness.

Regarding the additional covariates, the spatial econometric results do not provide evidence that FDI inflows foster the supply of renewable energy. Similarly, apart from two marginally significant positive indirect coefficients, patenting activity does not significantly increase renewable energy production, and therefore does not yet appear to be sufficiently targeted on renewable energy technologies. The estimates for the number of registered motor vehicles are in line with those of final energy use. This indicates that parts of the direct additional fuel demand is covered by renewable energy sources, while final energy demand reductions through indirect spatial effects affect renewable energies as well.

Despite the increased growth of the regional production of renewable energy since 2009 disclosed in Sect. 2, we find insignificant coefficients of the green growth binary in columns (10) and (12). Hence, following the launch of the national strategy, there has not been an additional (fixed) stimulus facilitating the production of renewables, other than the effects already captured through the explanatory variables. This also regards the nature

of the decomposed growth effects that has not changed.¹¹ Nevertheless, while the growth effect elasticities have not become greener since 2009, the absolute values of the income-related scale and technique effects generally increased, because per capita income has persistently grown, except for a short slowdown in 2009. Through this increase, the demand for clean energy and thus renewable energy production has been stimulated.

4.3 Robustness checks

To ensure the validity of results and specify their responsiveness to model changes, we carried out a number of robustness checks. Examples of results are presented for alterations of the base specification in Appendix B. Firstly, after conducting a robust Hausman test, we estimate the decomposed growth effects for final energy use and renewable energy production utilizing a fixed effects estimator as an alternative panel estimator. A fixed effects estimator can control for the determinants within provinces, but not for spatial interactions between provinces as well as simultaneity concerns. The results in Table 6 mostly support our findings for the direct effects. Specifically, the signs of the growth and trade effect elasticities remain unchanged, whereas their magnitudes are in parts different. For final energy use, changes in the significance levels can be observed in particular for the capital-labor ratio terms in columns (13) and (14). Interestingly, in columns (15) and (16), increases in FDI inflows are estimated to significantly increase renewable energy production, both in per capita form and per unit of GDP. Thus, according to the fixed effects estimations, foreign investors can partly contribute to the success of the green growth strategy. In contrast, the trade openness coefficients become significantly negative in columns (15) and (16), which we only detected for the indirect spatial effects on renewable energy production in Table 3.

Secondly, we apply alternative spatial weight matrices in order to check the sensitivity of our results to changes in the selected weights. As can be seen from the examples of results for per capita final energy use in Table 7, our main findings tend to remain unchanged, apart from several changes in the level of significance of the control variables. Interestingly, the magnitude of the indirect spatial interaction effect of the number of registered motor vehicles decreases with increasing threshold distance, and is insignificant from 100 km onwards. This indicates that spatial spillovers of fuel consumption of customers from nearby provinces on domestic energy use decrease with increasing distance. The negative direct effect of trade openness, which we also observed in several specifications in Table 1, becomes persistently significant for larger threshold distances as well as the first-order Queen contiguity matrix. In contrast, the marginally significant direct effect of the number of patent applications, found in column (2), cannot be validated. Hence, innovation activity may not be fully targeted at the sustainable reduction of energy use.

The results on trade openness and innovation activity in Table 7 are largely confirmed in Table 8, in which we carried out two additional robustness checks. That is, thirdly, instead of patent applications, we control for R&D expenditures that have also frequently been used to measure innovation activity (Hille & Möbius, 2019b; Shahbaz et al., 2020; Yu, 2012). Besides a potential missing sustainability focus of innovation activities, the insignificant coefficients of R&D expenditures $R\&D$ in columns (20) and (21) may also be explained by

¹¹ As mentioned before, the authors are happy to provide additional estimations of the first and fourth specification upon request.

a larger inaccuracy related to the fact that R&D expenditures as upstream inputs are further away from actual commercialized innovation than patent applications. Lastly, we analyzed a variety of alternative lag structures, because the effect of other explanatory variables than the income-induced technique effect may be subject to a lag, such as innovation activity (Hille & Lambernd, 2020). As an example, columns (22) and (23) display the results, when final energy use is analyzed as a moving average of the current year and the year $t+1$. Thus, potential lags are considered rather generally. A noticeable additional change in the estimates are the significantly negative direct effects of FDI inflows, suggesting that with some time delay foreign investments have been attracted that contribute to the reduction of per capita energy use and energy intensity.

5 Conclusion

Regional industrial clusters and initiatives have been important for the Korean economic development in general and the green growth strategy in specific, that has been implemented to reduce the country's risk, inter alia, through energy transition and a change of the pattern of production. In the light of this, we analyze the decomposed effects of regional economic growth on final energy use and renewable energy production using province-specific data. To provide a first evaluation of the regional-level effectiveness of the National Strategy for Green Growth, we test for general changes in the energy parameters as well as changes in the decomposed growth effects since 2009. Moreover, our results account for spatial spillover from nearby provinces.

We find that the scale and direct composition effect tended to increase both per capita final energy use and the final energy use intensity, outweighing reductions through the technique effect. Beyond the technique effect, the trade-induced composition effect reduced the energy parameters, suggesting that pollution offshoring has played a considerable role in the reduction of the Korean final energy use. When considering renewable energy production, we detect a positive impact of the scale and technique effect, and a negative impact of the direct and trade-induced composition effect. Specifically, the technique effect is found to be the main driver for increased renewable energy production. Regarding the paradigm shift through the green growth strategy, we detect no change in the decomposed growth effects since 2009. That is, the growth effect elasticities did not considerably change and become greener. Nonetheless, because of per capita income growth during the considered period, the absolute values of the regional, income-related scale and technique effects generally rose, so that, for example, renewable energy production strongly increased. Moreover, we find persistent spatial spillover effects, especially for the number of registered motor vehicles, highlighting the importance to consider spatial interactions as additional determinants of regional energy parameters.

Our results point out several issues to be considered by policy makers. Economic growth has been a double-edged sword, in particular for the development of per capita final energy use and energy intensity, where the income-related scale and technique effects are opposed. Thus, relying on economic growth only does not appear to be sufficient, and, given the current growth rates in Korea, would lead to rather slow improvements, if at all. Instead, adjusting the nature of future economic growth matters. In this context, crucial elements seem to be a stronger technique effect and the need to foster energy efficiency, in particular in Korea's capital-intensive sectors, to weaken the direct composition effect. This requires a stricter, yet balanced environmental policy, considering pollution reductions and industrial

competitiveness jointly. The effectiveness of the National Strategy for Green Growth to reduce final energy use and to foster the production of renewables on the regional level has so far been rather limited. Intensified supportive measures, that for instance induce higher investments in green innovation activity, and substantiated specific action plans regarding energy efficiency and renewable energy adoption for the near future, may help to change this and solve the seemingly difficult tradeoff. For example, the targeted share of renewable energy in the primary energy supply is still low compared to developed Western European countries and can be increased. To achieve this, the dominant public utilities could replace old power plants with renewable energy capacities more rapidly. As newly installed renewable energies often cost less than the cheapest generation options for fossil fuels (IRENA, 2020), public utilities may act as role models and lower Korea's dependence on fossil fuel imports at relatively low costs at once. From an international perspective, this may also help avoiding pollution offshoring to countries with lower pollution standards and energy prices. Overall, with regard to the goal of steering the nature of regional economic growth more towards reduced energy use and increased renewable energy production, the green growth strategy cannot yet be regarded as a success story. In order to reduce the long-term risks for the economy and to achieve the political objectives of the green growth strategy throughout the whole country and in a timely manner, a stronger commitment seems to be required.

Avenues for future research are manifold. First, considering the importance of the technique effect in reducing energy use and expanding renewable energy production, it may be promising to specify the influence of regulation-induced technological change. For instance, subject to data availability, the technique effect may be further decomposed (Barrows & Ollivier, 2018) or more granulated innovation measures may be adopted (Balsalobre-Lorente et al., 2018; Long et al., 2017). Second, based on Korean industry-, plant- or firm-level data, a detailed exploration of agglomeration effects will deliver additional insights into the relevance of both cluster policies and structural change. So far, spatial econometric analyses on the determinants of environmental pollution and energy use using more disaggregated data are the exception (Cole et al., 2013). Third, while our study focuses on the Korean green growth strategy, an application of this research design to other country samples may deliver interesting supplementary insights. During the past decade as well as following the adoption of the Paris Agreement in 2015, several developed and emerging countries initiated national regulatory frameworks to green their economy and improve the carbon emission balance, including Denmark's "Together for a greener future", France's "Stratégie Nationale Bas-Carbone" (SNBC) and Vietnam's "National Green Growth Strategy".

Appendix A: Overviews and specification tests

See Appendix Fig. 3 and Tables 4 and 5.



Fig. 3 Korean provinces

Table 4 LM and Moran's *I* test statistics

	Threshold distance of weight matrix		
	50 km	100 km	150 km
<i>Robust LM lag</i>			
<i>ENUSE/POP</i>	0.12	0.47	0.03
<i>ENUSE/GDP</i>	0.12	0.50	2.31
<i>RENEW/POP</i>	0.01	0.01	0.01
<i>RENEW/GDP</i>	0.03	0.01	0.04
<i>Robust LM error</i>			
<i>ENUSE/POP</i>	2.32	1.40	0.02
<i>ENUSE/GDP</i>	3.00*	2.17	0.13
<i>RENEW/POP</i>	5.65**	0.86	0.00
<i>RENEW/GDP</i>	5.61*	0.91	0.00
<i>Moran's I</i>			
<i>ENUSE/POP</i>	0.360***	0.089***	0.079***
<i>ENUSE/GDP</i>	0.350***	0.144***	0.084***
<i>RENEW/POP</i>	0.229***	0.076***	0.042***
<i>RENEW/GDP</i>	0.355***	0.154***	0.065***
<i>INC_{t-1}</i>	0.341***	0.046***	0.074***
<i>K/L</i>	0.271***	0.018**	0.033***
<i>TRADE OPENNESS</i>	0.487***	0.164***	0.178***
<i>CARS</i>	0.793***	0.362***	0.145***
<i>FDI</i>	0.426***	0.332***	0.124***
<i>PATENTS</i>	0.657***	0.408***	0.195***
<i>R&D</i>	0.660***	0.173***	0.138***

LM tests are based on the specification used in regressions (3), (7), (10), and (12)

* $p < 0.1$

** $p < 0.05$

*** $p < 0.01$

Table 5 Variables overview and descriptive statistics

Variable	Description	Unit	Mean	SD	Min	Max
<i>ENUSE/POP</i>	Per capita final energy use	Toe	5.308	5.884	1.284	23.217
<i>ENUSE/GDP</i>	Final energy use per unit of gross regional product	Toe per thousand Won (2010 prices) ^a	187.60	136.60	46.30	644.90
<i>RENEW/POP</i>	Per capita production of new and renewable energy	Toe	0.208	0.277	0.004	1.699
<i>RENEW/GDP</i>	Production of new and renewable energy per unit of gross regional product	Toe per thousand Won (2010 prices) ^a	7.370	8.450	0.181	46.400
INC_{t-1}	Per capita gross regional product lagged by one year	Thousand Won (2010 prices)	23,640	10,370	11,282	61,203
<i>K/L</i>	Ratio of physical capital stock to the number of people employed	Million Won (2010 prices) per employed person	158.97	41.25	87.54	280.88
<i>TRADE OPENNESS</i>	Sum of total imports and exports as a share of the gross regional product	Thousand Won per Won (2010 prices) ^a	643.20	512.10	17.50	2,905
<i>CARS</i>	Number of registered motor vehicles	Thousand	1,057	956.17	160.00	5,160
<i>FDI</i>	Foreign direct investment inflows	Billion Won (2010 prices)	595.14	1,323	0.000	9,204
<i>PATENTS</i>	Number of patent applications	Number	7,793	13,080	97.00	52,542
<i>R&D</i>	Total R&D expenditures	Million Won (2010 prices)	2,394,715	4,799,835	24,440	33,100,000

Binary variables are not displayed in the overview

^aIn the respective row, the descriptive statistics are multiplied with 10^6

Appendix B: Robustness tests

See Appendix Tables 6, 7 and 8.

Table 6 Fixed effects regression results

	$\ln(ENUSE/POP)$ (13)	$\ln(ENUSE/GDP)$ (14)	$\ln(RENEW/POP)$ (15)	$\ln(RENEW/GDP)$ (16)
$\ln INC_{t-1}$	-17.50*** (5.773)	-17.14*** (5.732)	-58.63** (21.86)	-58.27*** (21.41)
$\ln INC_{t-1}^2$	1.144** (0.409)	1.034** (0.417)	5.027*** (1.667)	4.916*** (1.634)
$\ln(K/L)$	7.347* (3.716)	6.046 (3.858)	59.30*** (17.66)	57.99*** (17.33)
$\ln(K/L)^2$	0.371 (0.327)	0.290 (0.346)	2.156 (1.748)	2.076 (1.724)
$\ln(K/L) \times \ln INC_{t-1}$	-1.070* (0.602)	-0.866 (0.642)	-8.069** (2.768)	-7.865** (2.725)
$\ln TRADE OPENNESS$	-0.056 (0.052)	-0.058 (0.056)	-0.561** (0.256)	-0.563** (0.255)
$\ln CARS$	0.269** (0.092)	0.213** (0.094)	1.719* (0.912)	1.663* (0.912)
$\ln PATENTS$	-0.044* (0.023)	-0.035 (0.025)	0.128 (0.202)	0.137 (0.205)
$\ln FDI$	-0.002 (0.004)	-0.002 (0.005)	0.044** (0.019)	0.044** (0.019)
Constant	67.37*** (20.66)	63.43*** (20.27)	117.0 (68.03)	113.0 (66.56)
Observations	272	272	272	272
R^2 within	0.725	0.674	0.761	0.644
R^2 between	0.221	0.377	0.024	0.157
R^2 overall	0.214	0.230	0.009	0.024
F -statistic	26.00***	14.79***	37.86***	21.45***
<i>Elasticities</i>				
Scale & technique	0.123		1.727	
Technique		-0.698		0.885
Composition	0.337	0.272	-0.104	-0.171
Trade	-0.056	-0.058	-0.561	-0.564

Robust standard errors in parentheses; results are obtained using a fixed effects estimator

* $p < 0.1$

** $p < 0.05$

*** $p < 0.01$

Table 7 Robustness tests using alternative spatial weight matrices

$\ln(ENUSE/POP)$	(17)		(18)		(19)	
	Weight matrix (threshold distance or contiguity)					
50 km	100 km		150 km		Contiguity	
X^a	WX^a	X	WX	X	WX	X
$\ln INC_{t-1}$	- 22.95*** (6.432)	1.072 (6.696)	- 3.516 (2.992)	- 22.38*** (6.256)	- 0.990 (3.020)	- 23.87*** (6.246)
$\ln INC_{t-1}^2$	1.539*** (0.426)	0.369 (0.544)	0.514*** (0.179)	1.536*** (0.409)	0.050 (0.265)	1.715*** (0.228)
$\ln(K/L)$	11.59*** (4.330)	1.676 (5.106)	2.343 (1.640)	11.01*** (3.899)	0.499 (2.300)	12.65*** (4.309)
$\ln(K/L)^2$	0.432** (0.183)	1.465*** (0.526)	1.115** (0.484)	0.583** (0.281)	- 0.031 (0.384)	0.836*** (0.257)
$\ln(K/L) \times \ln INC_{t-1}$	- 1.550*** (0.487)	- 1.647* (0.940)	- 1.351*** (0.503)	- 1.653*** (0.531)	- 0.010 (0.558)	- 2.057*** (0.591)
$\ln TRADE\ OPENNESS$	- 0.049 (0.033)	- 0.051 (0.041)	- 0.035* (0.021)	- 0.110*** (0.040)	- 0.003 (0.012)	- 0.127*** (0.037)
$\ln CARS$	0.234*** (0.058)	- 0.211*** (0.056)	- 0.073 (0.058)	0.234*** (0.082)	- 0.034 (0.046)	0.230*** (0.077)
$\ln PATENTS$	- 0.054* (0.027)	0.025 (0.036)	- 0.007 (0.024)	- 0.010 (0.026)	- 0.006 (0.013)	- 0.013 (0.028)
$\ln FDI$	- 0.003 (0.004)	- 0.002 (0.003)	0.0003 (0.003)	- 0.0004 (0.004)	- 0.002** (0.001)	- 0.003 (0.003)
Constant	74.63** (37.08)	119.5** (50.05)	102.6* (57.51)	113.5*** (43.55)		113.5*** (43.55)
Observations	272	272	272	272		272

Table 7 (continued)

In (<i>ENUSE/POP</i>)	(2)		(17)		(18)		(19)	
	Weight matrix (threshold distance or contiguity)							
	50 km		100 km		150 km		Contiguity	
	X^a	WX^a	X	WX	X	WX	X	WX
Log-likelihood	379.41		371.87		373.48		375.90	
Wald test	5.004***		543.31***		3,049***		1,190***	
F-statistic	312.77***		36.22***		203.29***		79.31***	

Robust standard errors are in parentheses; difference GMM is used to estimate the specifications

* $p < 0.10$

** $p < 0.05$

*** $p < 0.01$

^a X refers to the non-spatially weighted explanatory variables and WX to the spatially weighted explanatory variables

Table 8 Robustness tests using moving average energy use and controlling for R&D expenditures

	ln (ENUSE/POP)		ln (ENUSE/GDP)		ln (ENUSE/POP) _{MOV,AV}		ln (ENUSE/GDP) _{MOV,AV}	
	(20)	WX ^a	(21)	WX	(22)	X	(23)	X
ln INC_{t-1}	- 22.72*** (6.468)	1.190 (7.589)	- 22.06*** (6.279)	4.172 (7.752)	- 20.10*** (7.165)	X	- 19.93*** (6.595)	X
ln INC_{t-2}	1.593*** (0.451)	0.435 (0.621)	1.453*** (0.433)	0.186 (0.649)	1.286*** (0.467)	X	1.204*** (0.439)	X
ln (K/L)	12.21*** (4.563)	2.567 (6.011)	10.30*** (4.372)	- 0.147 (6.061)	9.292** (4.711)	X	7.997* (4.531)	X
ln (K/L) ²	0.622** (0.266)	1.657*** (0.598)	0.512** (0.237)	1.489*** (6.663)	0.225 (0.177)	X	1.582*** (0.198)	X
ln (K/L) × ln INC_{t-1}	- 1.823*** (0.575)	- 1.933* (1.094)	- 1.527*** (0.540)	- 1.499 (1.153)	- 1.117** (0.510)	X	- 2.117** (1.040)	X
ln TRADE OPENNESS	- 0.076*** (0.029)	- 0.054 (0.038)	- 0.067** (0.028)	- 0.026 (0.041)	- 0.067* (0.037)	X	- 0.045 (0.035)	X
ln CARS	0.182*** (0.054)	- 0.245*** (0.050)	0.116** (0.056)	- 0.354*** (0.053)	0.268*** (0.061)	X	0.156*** (0.066)	X
ln PATENTS						X		X
ln R&D	0.055 (0.040)	0.039 (0.027)	0.011 (0.041)	0.020 (0.034)		X		X
ln FDI	- 0.006 (0.004)	- 0.003 (0.003)	- 0.006 (0.004)	- 0.003 (0.003)		X		X
Constant	68.77* (38.27)		57.16 (39.43)		77.40* (41.46)	X	58.22 (41.83)	X

Table 8 (continued)

	$\ln(ENUSE/POP)$	$\ln(ENUSE/GDP)$	$\ln(ENUSE/POP)_{MOV,AV}$	$\ln(ENUSE/GDP)_{MOV,AV}$
	(20)	(21)	(22)	(23)
X^a	WX ^a	WX	X	X
Observations	272	272	272	272
Log-likelihood	369.29	368.25	403.39	385.95
Wald test	218,179***	1,691***	18,358***	154,110***
F-statistic	13,636***	105.71***	1,147***	9,632***

Robust standard errors are in parentheses; difference GMM is used to estimate the specifications

^aX refers to the non-spatially weighted explanatory variables and WX to the spatially weighted explanatory variables

* $p < 0.10$

** $p < 0.05$

*** $p < 0.01$

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