Greening the Future: Dynamics of Green Innovation in Korea through Patent and Policy Synergies

Ihsen Abid
Department of Finance, College of Business, Imam Mohammad Ibn Saud Islamic University (IMSIU), Riyadh, Saudi Arabia
isbaklouti@imamu.edu.sa (corresponding author)

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ABSTRACT

Green innovation is measured by Environment-Related Patent Applications (ERPA) and analyzed in relation to Information and Communication Technology Imports (ICTI), Research and Development Expenditure (RDE), Environmental Policy Stringency (ENV), Gross Domestic Product per capita Growth (GDPG), and Population Growth (PG). This study examines the determinants of green innovation in South Korea from 1990 to 2023. It uses a time-series econometric approach with a Vector AutoRegression (VAR) model. Analytical methods include Impulse Response Functions (IRFs), Forecast Error Variance Decomposition (FEVD), Granger causality tests, and a Vector Error Correction Model (VECM) to capture both short-run dynamics and long-run equilibrium relationships. ICTI consistently has a positive and significant effect on green innovation, emphasizing the importance of international technology transfer. GDPG is positive in the short run but negative over the long run. Stricter environmental policies initially have a negative effect, but this reverses over time, indicating the need for flexible policy adjustments. PG has a positive long-run effect, while RDE exhibits weak or delayed impacts. This research contributes to the literature by offering a comprehensive time-series analysis of the factors driving green innovation in a developed Asian economy. It highlights the importance of technology openness, adaptive regulation, and macroeconomic factors in fostering green innovation.

Keywords-green innovation; ICTI; environmental policy stringency; VECM; patent applications

I. INTRODUCTION

The urgent need to shift towards environmentally sustainable development has placed green innovation at the top of national policy priorities. In South Korea, a highly industrialized and export-driven economy, the dynamic interplay between environmental regulation, technological advancements, and economic growth has garnered increasing attention from academics and policymakers. Green innovation, which involves creating and disseminating technologies that reduce environmental impact, is crucial for meeting climate objectives, enhancing resource efficiency, and sustaining long-run global competitiveness. The existing literature agrees that leveraging better technologies, materials, machinery, processes, or products can effectively protect the global environment [1].

South Korea's government has demonstrated a strong commitment to sustainability through initiatives like the Green New Deal and carbon neutrality pledges. In the mid-2000s, the government recognized green energy and industries as a key long-run economic priority. To promote the greening of the economy, it introduced green policies and visions for sustainable growth. This review highlights the decade-long Research and Development Investment (RDI) by the Korean government in greening the economy [2]. However, the success of these efforts depends on the country's capacity to foster innovation in environmental technologies. Previous studies have emphasized the dual role of regulatory frameworks and market dynamics in shaping innovation outcomes [3]. The influence of ICTI as facilitators of technology transfer, the stringency of environmental policies, and the availability of targeted innovation finance are crucial factors in determining the capacity for green innovation. Despite these theoretical insights, empirical validation remains necessary, particularly within the specific institutional and economic context of South Korea. This study fills this gap by examining the factors that drive green innovation. It examines the influence of ICT goods imports, environmental policy stringency, RDI, and population growth on green patent applications, a proxy for green innovation, from 1990 to 2023. The results provide evidence-based insights for policymakers seeking to develop integrated strategies that balance environmental sustainability with technological progress and economic development [4].

II. LITERATURE REVIEW

The determinants of green innovation have garnered significant attention in the academic literature, particularly in the context of South Korea's rapid industrialization and evolving environmental policy. South Korea is among the few countries that allocate more than 3% of their GDP to Research and Development (R&D), as measured by the Gross Domestic Expenditure on R&D (GERD) index. This high level of R&D investment provides a strong foundation for national innovation capacity and patenting activity. It has positioned Korea as a global leader in technological advancements and green patents, as evidenced by recent empirical data [5]. A strong R&D commitment enhances the country's capacity to integrate environmental goals into its innovation system.

A. ICT Goods Imports and Technological Diffusion

The import of ICT goods facilitates international technology diffusion, which in turn stimulates innovation capacity, including environmentally oriented technologies [6]. According to [7], the inflow of foreign technologies supports the absorptive capacity of domestic firms and fosters innovation spillovers in newly industrialized economies, such as South Korea. Similarly, the author in [8] finds that the increased penetration of ICT infrastructure is closely linked to green innovation in East Asia, primarily due to enhanced information flows and the transfer of technical know-how.

B. R&D Expenditure and Innovation Output

RDI has historically been recognized as a key driver of green innovation [9]. South Korea's significant R&D investment, which surpasses 3% of GDP, directly enhances its ability to produce high-value green patents and promotes vibrant innovation ecosystems. In [10], the authors identify various types of green innovators in Korea and highlight that public R&D policies significantly enhance innovation in energy and waste reduction technologies. They also emphasize that R&D's impact may not be immediate, suggesting there could be lag effects. Additionally, studies highlight the long-run, sustainability-adjusted benefits of public investment in innovative sectors, underscoring R&D's positive contribution [11].

C. Environmental Policy Stringency

The Porter Hypothesis, as outlined in [4], suggests that well-designed environmental regulations can stimulate innovation, potentially offsetting compliance costs and enhancing competitiveness. However, empirical findings remain mixed [12], and the author of [13] cautions that excessively stringent regulations may hinder innovation incentives, particularly when firms operate under high uncertainty or lack sufficient technical capacity. In the South Korean context, authors in [14] find that moderate environmental regulation has a positive influence on green patenting, but overly restrictive policies may result in compliance-driven innovation.

D. Economic Growth and Innovation

The relationship between economic development and green innovation is complex. Authors in [15] find that while higher GDP enables greater innovation spending, it can also increase carbon emissions unless paired with strict environmental governance. In South Korea, sustained economic growth has been accompanied by an explicit policy emphasis on environmental sustainability and innovation, leveraging substantial R&D investment to promote green patenting and decouple economic growth from environmental degradation [16]. Nonetheless, the decoupling process has been gradual, with green innovation often driven more by policy and trade pressures than by income changes alone [17].

E. Population Growth and Innovation Pressure

Population growth increases environmental stress and demand for sustainable solutions [18]. According to [19], growing populations in Korea have led to increased municipal spending on energy and transportation systems. This demographic pressure serves as a structural force promoting long-term green innovation.

III. METHODOLOGY

This study investigates the factors influencing green innovation in South Korea. To capture both short-run dynamics and long-term relationships among the variables, a multistage econometric approach is employed. To ensure the validity of time-series estimations, unit root tests are conducted to examine the stationarity of each variable. Non-stationary variables can produce spurious regression results unless they are first differenced [20]. The Augmented Dickey-Fuller (ADF) test [21] is applied to determine whether a variable is integrated of order zero (0) or one (1). A VAR model was estimated to analyze the dynamic interdependencies among the variables. This method treats all variables as endogenous and models each as a linear function of its lags and the lags of the other variables [22]. The optimal lag length was determined using the Akaike Information Criterion (AIC) to minimize the risk of model misspecification.

To interpret the VAR results, IRFs were derived. IRFs trace the time path of the dependent variable, green innovation, in response to a one-standard-deviation shock to each of the explanatory variables [23]. In addition, FEVD was conducted to quantify the relative contribution of each shock to the forecast error variance of green innovation across different time horizons. Granger causality tests were employed to examine whether lagged values of one variable contribute to the prediction of another. This test captures short-run causal linkages, which are crucial for analyzing directional effects among variables [24]. If cointegration relationships were identified using the Johansen cointegration test [25], a VECM was estimated. This model allows for the distinction between short-run dynamics and long-run equilibrium relationships among the variables. The Error Correction Term (ECT) indicates the speed at which the system adjusts back to equilibrium following a deviation. To ensure the robustness of the model, diagnostic tests were conducted to assess serial correlation, residual normality, and overall model stability.

IV. DATA

This study examines the determinants of green innovation in South Korea from 1990 to 2023, with a particular focus on the development of environmental technologies. It utilizes annual country-level data obtained from reputable international sources, including the Organization for Economic Co-operation and Development (OECD) and the World Bank. The selected variables capture innovation outputs and inputs, the regulatory environment, and key socio-economic conditions. All variables were transformed into natural logarithms to reduce heteroscedasticity and facilitate interpretation of the estimated coefficients. The dependent variable, Patent Applications in Green Technologies (PATG), captures the number of patent filings in environmentally related technological domains. It is used as a proxy for green innovation output at the national level, indicating the country's progress in developing technologies essential for environmental sustainability.

To investigate the drivers of green innovation, three independent variables are employed. First, RDE as a percentage of GDP is used as a proxy for innovation input, capturing the level of domestic investment in R&D activities. Second, ICT goods imports as a share of total goods imports (ICTI) indicate the degree of access to external digital technologies, which can facilitate innovation processes. Third, the ENV Index quantifies the strength of environmental regulations on a scale from 0 (least stringent) to 6 (most stringent), serving as a proxy for regulatory pressure and policy-driven innovation incentives. In addition, two control variables are included to account for structural and demographic influences. GDPG, expressed as an annual percentage, controls economic size and potential innovation market scale. Population growth (POPG), also measured annually, serves as a proxy for demographic pressure and the prospective demand for green technologies.

Descriptive statistics (Table I) summarize the distribution and variability of the key variables. The dependent variable, PATG, displays considerable variation over the study period, capturing fluctuations in green innovation output. Among the explanatory variables, RDE reveals a generally increasing but uneven trend in innovation-related investment. ICTI suggests a persistent reliance on imported digital technologies, which could potentially enhance domestic innovation processes. ENV shows significant changes in regulatory stringency, likely reflecting both national policy shifts and international environmental commitments. Regarding the control variables, GDPG captures substantial macroeconomic fluctuations, including periods of recession and recovery, such as those associated with financial crises. POPG indicates varying demographic trends that may influence innovation demand, workforce composition, and market potential for environmentally related technologies.

TABLE I. DESCRIPTIVE STATISTICS

Variable	Obs	Mean	Std. dev.	Min	Max
PATG	33	8.5137	1.3302	5.1808	9.825
RDE	27	1.1495	0.3116	0.7010	1.6507
ICTI	23	2.6730	0.2147	2.2814	3.0722
ENV	33	0.3970	1.0022	-2.4849	1.284
GDPG	34	4.1841	3.2845	-5.8118	10.6775
POPG	34	0.5806	0.3267	-0.1875	1.0392

To evaluate the stationarity properties of the variables, the ADF test was employed. The results show that PATG and GDPG are stationary at the level, with p-values of 0.0475 and 0.0025, respectively. Conversely, RDE, ICTI, ENV, and POPG are non-stationary in levels, as their p-values surpass typical significance thresholds. Nonetheless, all four variables become stationary after first differencing, confirming they are integrated of order one. These results support the use of cointegration techniques and the estimation of an error correction model in further analysis.

V. RESULTS

A. VAR Estimation Results

The optimal lag length was determined to ensure model adequacy and to prevent overfitting. For the VAR model, a lag order of two was selected because it minimized the Final Prediction Error (FPE), the AIC, and the Hannan–Quinn Information Criterion (HQIC). This selection was strongly supported by the likelihood ratio (LR) test (LR statistic = 96.13, p-value = 0.00), indicating that this specification outperformed models with fewer lags. The VAR estimation results for the dependent variable (PATG) reveal several statistically significant relationships (Table II).

TABLE II. VAR MODEL RESULTS FOR PATG EQUATION

Variable (Lag)	Coefficient	Std. error	p-value
PATG (L1)	1.0015	0.1541	0.0000
PATG (L2)	-0.3807	0.1454	0.0090
DRDE (L1)	0.7545	2.0021	0.7060
DRDE (L2)	3.6722	1.9901	0.0650
DICTI (L1)	1.4983	0.5986	0.0120
DICTI (L2)	0.3343	0.6215	0.5910
DENV (L1)	-0.9188	0.4763	0.0540
DENV (L2)	0.1595	0.4055	0.6940
GDPG (L1)	-0.0028	0.0264	0.9160
GDPG (L2)	0.1084	0.0360	0.0030
DPOPG (L1)	-0.1839	0.2662	0.4900
DPOPG (L2)	-0.6544	0.3067	0.0330
Constant	3.1027	1.1522	0.0070

The first lag of PATG is positive and statistically significant, indicating strong persistence in green innovation over time. In contrast, the second lag of PATG is significantly negative, implying a partial reversal in patenting activity. Among the explanatory variables, the first lag of differenced ICTI (DICTI) exhibits a significant positive impact on green patenting, indicating that increased access to imported digital technologies promotes environmental innovation. Additionally, the second lag of GDPG has a positive relationship, indicating that economic growth supports green innovation after a delay. Differenced ENV (DENV) has a marginally significant adverse effect at the first lag, suggesting that stricter regulations may initially hinder innovation, possibly due to adjustment costs or compliance challenges. Finally, Differenced POPG (DPOPG) is negatively related at the second lag, implying that demographic pressures may reduce green innovation over the medium term.

The stability and adequacy of the VAR model were evaluated using standard diagnostic procedures (Table III). Stability tests confirmed that all eigenvalues lie within the unit circle, indicating dynamic stability of the VAR specification. Additional diagnostic checks for autocorrelation, residual normality, and heteroskedasticity further validated the model's specification and confirmed its suitability for subsequent analysis.

TABLE III. VAR STABILITY AND DIAGNOSTIC TESTS

Eigenvalue stability condition		
#	Eigenvalue	Modulus
1	-0.5050341 + 0.6447401i	0.8190
2	-0.5050341 - 0.6447401i	0.8190
3	0.3243856 + 0.7152363i	0.7854
4	0.3243856 - 0.7152363i	0.7854
5	0.0612608 + 0.7654937i	0.7679
6	0.0612608 - 0.7654937i	0.7679
7	0.6885878 + 0.2940064i	0.7487
8	0.6885878 - 0.2940064i	0.7487
9	-0.1156531 + 0.5248409i	0.5374
10	-0.1156531 - 0.5248409i	0.5374
11	-0.4745374 + 0.1825939i	0.5085
12	-0.4745374 - 0.1825939i	0.5085
Diagnostic test results		
Test	Statistic	p-value
Breusch-Godfrey	3.2360	0.1983
Breusch-Pagan / Cook-Weisberg	0.6800	0.4112
Shapiro-Wilk	0.9237	0.1165

IRFs illustrate the dynamic effects of a one-standard-deviation shock to each independent variable on green innovation over time (Figure 1). The results indicate that green innovation in South Korea responds differently to various shocks. Stricter environmental policies initially hinder innovation but subsequently lead to a rebound, suggesting adaptive responses by firms. Imports of information and communication technology goods consistently promote green patenting, underscoring the role of technology diffusion. Population growth exerts a negative influence on innovation, whereas research and development (R&D) expenditure has a delayed but positive impact. Economic growth provides moderate support for innovation, and past innovation exhibits strong persistence. Overall, these findings underscore the complex and dynamic nature of green innovation.

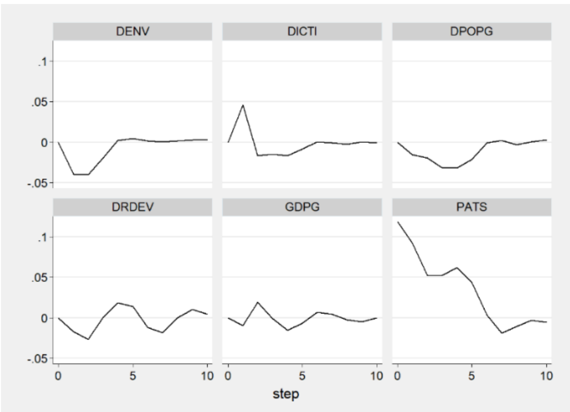

Fig. 1. Impulse Response Functions for PATG

Table IV presents the FEVD results for the response variable PATG in response to the independent variable impulses. The results indicate that while patents are mainly influenced by their past values, over time, technological investments (ICTI), environmental R&D, and, to a lesser extent, economic growth indicators begin to have a significant impact on patent dynamics. This supports the idea that sustained innovation is not only path-dependent but also shaped by broader systemic investments in R&D and technology.

TABLE IV. FORECAST ERROR VARIANCE DECOMPOSITION

Step	**PATG**	**dRDE**	**dICTI**	**dENV**	**GDPG**	**dPOPG**
1	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.8415	0.0111	0.0789	0.0568	0.0031	0.0086
3	0.7696	0.0303	0.0727	0.0951	0.0139	0.0184
4	0.7541	0.0268	0.0699	0.0942	0.0123	0.0428
5	0.7437	0.0314	0.0669	0.0817	0.0163	0.0600
6	0.7419	0.0338	0.0645	0.0774	0.0163	0.0661
7	0.7389	0.0366	0.0642	0.0771	0.0173	0.0658
8	0.7349	0.0434	0.0633	0.0760	0.0175	0.0649
9	0.7353	0.0433	0.0632	0.0758	0.0176	0.0649
10	0.7331	0.0455	0.0630	0.0757	0.0180	0.0647

The Granger causality Wald test evaluates whether past values of specific variables can predict changes in green innovation, measured by environmental patents. The results indicate that digital technology access (p-value = 0.043) and economic growth (p-value = 0.001) significantly Granger-cause green innovation, suggesting that progress in these areas can effectively promote environmental patenting activity. Conversely, research and development expenditure, environmental regulation strictness, and population growth do not demonstrate statistically significant causal effects at standard levels. These findings support policies that enhance digital infrastructure and foster economic development as strategies to promote green innovation.

B. VECM Estimation Results

The Johansen cointegration test and diagnostics were performed to examine the long-term equilibrium relationships among the variables. The results confirm the presence of two significant cointegrating vectors, as indicated by the trace statistics surpassing their respective critical values at ranks 0 and 1. Additionally, the diagnostics for the cointegrating equations further support this finding, with highly significant chi-square statistics (p-values = 0.00). These findings validate the existence of stable long-term relationships and support the use of a VECM framework for further analysis.

To examine the structural dynamics behind green technological innovation in Korea, the cointegration vector from the VECM offers insights into the long-term relationships among the variables (Table V). The cointegration vector is normalized on PATG, as it represents the primary dependent variable of interest: green innovation output, measured through environmental patent applications.

TABLE V. LONG-RUN COINTEGRATION VECTOR

Variable	**Coefficient**	**Std. error**	**p-value**
PATG	1.0000	–	–
RDE	0.0000	–	–
ICTI	210.4778	22.0158	0.0000
ENV	–72.5015	13.3848	0.0000
GDPG	–18.3362	3.0350	0.0000
POPG	175.4085	23.8174	0.0000
Constant	–465.5138	–	–

The cointegrating equation for green innovation indicates that ICTI has a strong positive impact, suggesting that increased access to external digital technologies significantly enhances the country's capacity for green innovation. ENV displays a negative long-term relationship. Although it may seem counterintuitive, this suggests that overly strict regulations could hinder innovation unless supported by other policy measures. GDPG also has a negative long-term effect, possibly indicating a delay between economic growth and its translation into green innovation output. POPG has a positive and significant contribution, implying that larger and growing populations can create demand pressures or market opportunities that promote the development of green technologies. Table VI presents the short-term dynamics of changes in green innovation output (ΔPATG), where ΔPATG represents the first difference of PATG, indicating the annual change in environment-related patent filings, as derived from the VECM framework.

TABLE VI. VECM SHORT-RUN DYNAMICS FOR ΔPATG

Regressor	Coefficient	Std. error	p-value
ce1 (L1.)	–0.7404	0.2431	0.0020
ce2 (L1.)	1.1824	0.3893	0.0020
ΔPATG (LD.)	0.6596	0.2345	0.0050
ΔRDEV (LD.)	–1.3117	2.6260	0.6170
ΔICTI (LD.)	0.6623	0.6427	0.3030
ΔENV (LD.)	1.0612	0.4022	0.0080
ΔGDPG (LD.)	–0.0619	0.0262	0.0180
ΔPOPG (LD.)	–0.2073	0.3456	0.5490
Constant	–0.2500	0.1789	0.1620

The error correction terms are both significant at the 1% level. The ΔPATG has a substantial and positive effect, suggesting that past short-term changes in green innovation positively influence current changes, possibly due to momentum or path dependence in innovation behavior. Among the independent variables, the first difference of ENV (ΔENV) has a positive and significant effect, indicating that stricter regulations in the short run stimulate green patent activity. In contrast, the first difference of GDPG (ΔGDPG) has a negative short-run impact, implying that while sustained long-term growth is beneficial, short-term economic fluctuations may temporarily constrain innovation activity. Other variables, including the ΔICTI, ΔRDEV, and ΔPOPG, are not statistically significant in the short run, suggesting that their effects may manifest over the longer term rather than in the immediate adjustment period.

VI. DISCUSSION

The study's findings provide strong empirical support for the impact of access to digital technology, economic factors, regulatory environments, and demographic trends on environmental innovation. These results reinforce the theoretical foundations mentioned earlier, especially highlighting the importance of R&D intensity and Korea's robust GERD index in promoting green patenting performance.

Digital Technology Access and Green Innovation: One of the most consistent findings across the analyses is the positive influence of ICTI on green innovation. This supports prior studies that emphasize the significance of technological diffusion as a driver of domestic innovation [7]. The positive and statistically significant short- and long-term effects of ICTI align with similar studies, which show that access to foreign technology encourages knowledge spillovers and boosts domestic innovation [26]. ICTI often acts as an enabler for research, prototyping, and the commercialization of green technologies by integrating external capabilities into local systems. This also aligns with South Korea's national strategy to utilize ICT imports to strengthen innovation ecosystems and enhance environmental performance.

Environmental Policy Stringency and Innovation: This study provides detailed insights into the impact of environmental policy stringency. In the short term, tighter regulations appear to hinder green innovation slightly, likely due to compliance costs and transitional challenges [27]. However, in the VECM framework, shifts in ENV in the short run significantly promote innovation, indicating that firms react adaptively to policy adjustments. The long-term impact, on the other hand, is negative, suggesting that excessively strict regulatory environments may suppress innovation unless supported by complementary measures, such as subsidies, tax credits, or infrastructure support [28]. This mixed evidence aligns with earlier findings in the Korean context, where moderate environmental regulation has been found to boost green patenting. At the same time, overly strict policies might result in compliance-driven rather than transformative innovation [29].

Economic Growth and Innovation Linkages: GDPG exhibits a complex relationship with green innovation [30]. The short-term positive Granger causality and impulse response demonstrate that economic growth promotes innovation through increased investment and institutional capacity. However, the VECM long-term coefficient is negative, indicating diminishing returns or structural mismatches between economic growth and the development of green technology. This aligns with earlier studies [31], which highlight that while economic growth enables higher spending on innovation, it does not automatically lead to greener outcomes unless paired with targeted environmental policies and market incentives.

Population Dynamics: POPG has a statistically significant adverse effect on green innovation in the short term but a positive impact in the long run [32]. The long-term positive relationship may reflect market growth and increased demand for environmentally sustainable solutions, which can encourage innovation. Short-term adverse effects could result from heightened environmental stress, resource reallocation, and policy strain, consistent with findings from demographic-environment interaction studies [33]. This suggests that the structural pressure resulting from population growth drives innovation initiatives at both the municipal and national levels.

R&D Expenditure: The RDE does not show a strong influence on green innovation in the short term or through Granger causality. Its effect only appears in the FEVD results at later stages, indicating a delayed but gradually growing impact. This finding supports earlier discussions on the lagged effects of R&D and highlights the importance of sustained, long-term investment strategies to achieve measurable environmental innovation results. The implication is that consistent and well-targeted R&D policies are essential for long-term innovation success [34]. Additionally, these findings highlight the crucial role of Korea's high GERD index in laying the groundwork for eventual innovation benefits, even if the immediate effects are not evident.

VII. CONCLUSION

This study combines empirical findings with a solid theoretical foundation, highlighting South Korea's robust commitment to R&D and its supportive policy environment. The data indicate that ICT imports and macroeconomic factors primarily drive green innovation in South Korea (1990–2023). Digital technology inflows greatly enhance green patenting, while R&D investment has a delayed but positive impact. Economic growth and environmental policies have mixed effects, underscoring the need for balanced and flexible strategies. These findings support previous research that highlights the importance of targeted policy support and the complementary role of market mechanisms. Based on these findings, policy measures should focus on reducing barriers to the imports of ICT goods, promoting international collaborations, and providing targeted support for green R&D initiatives. Regulatory frameworks should maintain a balance between enforcement and incentives, consistent with the Porter Hypothesis. Long-term funding mechanisms for integrated urban planning, coupled with dedicated support for green small and medium-sized enterprises (SMEs), are essential to sustain innovation momentum. Finally, adaptive governance that leverages real-time indicators will help ensure that environmental innovation remains both responsive to emerging challenges and resilient over time.

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