The Information Revolution, Innovation Diffusion and Economic Growth: An Examination of Causal Links in European Countries

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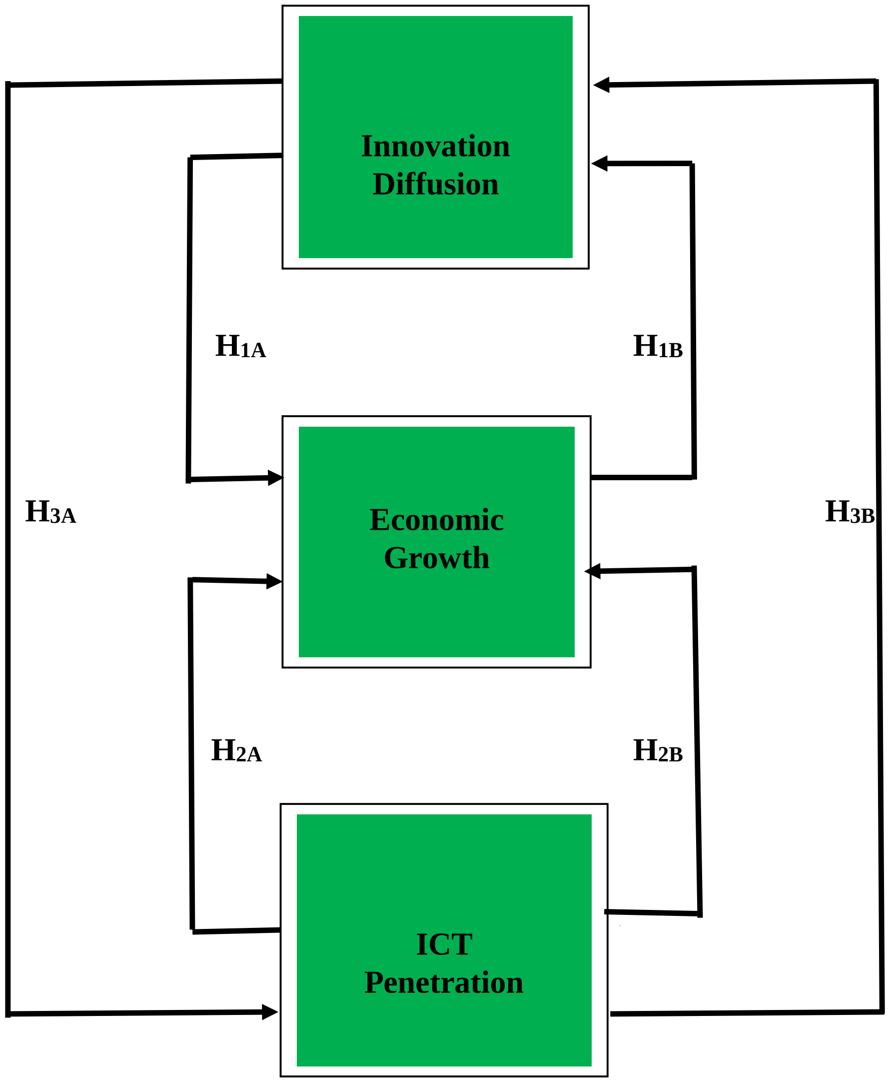
RESEARCH HIGHLIGHTS

- The interactions among the diffusion of innovation, ICT penetration, and economic growth are considered.
- The focus is on European countries over 1961-2016.
- A dynamic panel model is used for the empirical investigation.
- Although the results are not uniform, overall there is Granger causality among the variables.

GRAPHICAL ABSTRACT FOR REVIEW



Notes:

H_{1A}: Innovation diffusion Granger-causes economic growth.

H_{2A}: ICT penetration Granger-causes economic growth.

H_{3A}: ICT penetration Granger-causes innovation diffusion.

Subscript B (in place of A) signifies Granger causality in reverse order.

Abstract

Over the last five decades, the economic landscape in Europe has been transformed rapidly due to innovation, digitisation of the economy, and emergence of new sources of growth. However, the complex dynamics among diffusion of innovation, penetration of information and communication technology (ICT), and economic growth have not been adequately studied. This paper investigates the relationships among these three variables for European countries over 1961-2016. The goal is to determine whether the direction of causality among the variables runs both ways, one way, or not at all. Using a vector error-correction model, we find that in the long run, both innovation diffusion and ICT penetration stimulate economic growth. In the short run, however, the causal links are not always uniform and depend on proxies that are used for innovation diffusion and ICT penetration. The results provide valuable insights on the types of policies and strategies that would sustain economic growth in European economies.

Keywords: Innovation diffusion, ICT penetration, economic growth, VECM

JEL Classification : O43, O16, E44, E31

1. Introduction

Economic growth in Europe has undergone unprecedented transformation over the last five decades. Many of these European economies experienced significant economic growth while others have experienced lower productivity and economic growth rates (Veugelers, 2017). Key drivers of economic growth in Europe have received considerable attention in the literature. Among the possible drivers of economic growth, innovation has and continues to receive considerable attention (Hudson and Minea, 2013). This relationship has been explored at least as far back as Schumpeter (1911, 1939) who recognized that the innovations of the industrial age contributed to economic well-being. Innovation continues to be linked to higher productivity, growth, and development at not only the firm-level, but also on a macroeconomic level (e.g., Andergassen et al., 2017; Kaplinsky et al., 2009; Fagerberg, 2005). Given its potentially high impact on socioeconomic development of various economic agents and countries, innovation has been an intriguing research topic for academics as well as policymakers.

The field of information systems (IS) has also been very interested in the impact of innovation in transforming the information and communication technology (ICT) industry and adoption behavior of ICT among all stakeholders in the economy (see, *inter alia*, Malerba and Brusoni, 2007; Freeman and Soete, 1997; Grossman and Helpman, 1994). With ICT becoming ubiquitous over the past few decades, the impact of ICT on a number of aspects of innovation is increasing (see, for instance, Jha and Bose, 2016; Avgerou, 2008). Increasing discoveries and technological innovations in the ICT industry, especially new discoveries in increasing the computational speed, enhancing the sophistication of ICT devices and reducing the cost of ICT infrastructure and services, have had a major impact on greater prevalence of ICT among the various economic agents. These new technological innovations have also spawned new user-friendly ICT devices and services, all of which have further elevated ICT penetration rates among all economic agents.

Various studies have considered the nexus between innovation and economic growth (see, for instance, Hasan and Tucci, 2010). These studies have focused on different countries, time periods, modelling techniques, and proxies for innovation. The Granger causality test has been extensively utilized to study the direction of causality between innovation and economic growth. However, studies on the innovation-growth nexus produced inconclusive results. These studies do not show consensus on either the existence or the direction of the Granger causality between the variables. One of the major reasons for the absence of consensus in the results of past studies is that the Granger causality test, in a bivariate framework, is likely to be biased due to the omission of relevant variables affecting the innovation-growth nexus (see, for instance Maradana et al., 2017).

Accordingly, in recent literature, there are a few studies that investigate the innovation-growth linkage in a multivariate framework by including different macroeconomic variables to establish whether innovation actually causes economic growth and development (see, *inter alia*, Pradhan et al., 2017b; Pradhan et al., 2016c; Agenor and Neanidis, 2015; Galindo and Mendez, 2014; Cetin, 2013; Kirchhoff et al., 2007; Hassan and Tucci, 2010). Adding to the literature, the present study will investigate the debated innovation-growth nexus in the presence of ICT penetration, as the latter is a key link to both innovation diffusion and economic growth (see, *inter alia*, Spanos et al., 2002; Cardona et al., 2013; Dutta et al., 2007; Bayo-Moriones and Lera-Lopez, 2007; Dedrick et al., 2003).

The importance and relevance of the innovation diffusion, ICT penetration, and economic growth nexus arises from the potential high impact that ICT penetration might have on social and economic development (see, for instance, Cuervo and Menendez, 2006; OECD, 2005). Explicitly, penetration of ICT[1] is the backbone of the knowledge economy and in recent years has been recognized as an effective tool for enhancing economic growth and sustainable development. In addition to improving the efficiency of firms, ICT penetration might also facilitate and drive innovations in terms of both processes and products/services. Given this potential, ICT penetration might be valuable as innovation becomes increasingly important in modern economies, thus heightening the performance or prosperity of firms, industries, and nations (Arvanitis et al., 2013; OECD, 2010). With relatively low usage costs and the ability to overcome distance, ICT has revolutionized the transfer of information, knowledge, and technology around the world (see, for instance, Chen and Kee, 2005). The above discussion and reasoning indicate that ICT penetration[2] can enhance innovation and economic growth of an economy. In addition, the possibility of the existence of joint interdependence between these three variables needs to be researched.

The primary objective of this study is to examine the short-term and long-term dynamics between innovation, ICT penetration, and economic growth in Europe where there has been considerable variation in economic growth among the countries. The study

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[1] ICT penetration in an economy refers to the accessibility, reliability and efficiency of computers, phones, televisions and radio sets, and the various networks that link them. The World Bank group defines ICT to consist of hardware, software, networks, and media for collection, storage, processing transmission, and presentation of information in the form of voice, data, text, and images. They range from the telephone, radio and television to the internet (World Bank, 2003a,b).

[2] ICT mutually affects innovation and economic growth both at a micro-level (see, for instance, Wong et al., 2016; Mithas et al., 2011) as well as a macro-level (see, for instance, Pradhan et al., 2017b; Zhang and Li, 2018; Sassi and Goaied, 2013; Vu, 2013; Spanos et al., 2002).

uses a wide range of measures for innovation diffusion and ICT penetration; it shows that there are cointegration relationships between these three variables. In particular, the paper shows that there is strong evidence that innovation and ICT penetration contribute to economic growth in the long run. The short-run dynamics also show that there is strong inter-dependence between these variables. The long-run and short-run relationships between these variables provide valuable insights on the types of *co-development* policies that are required to propel economic growth in Europe.

The paper consists of five sections. The second section offers a concise survey of the related empirical literature and highlights the contributions of this study. The third section defines the data, variables, and methodology. The fourth section presents the empirical results. The final section provides a detailed discussion of the results. It also offers our conclusions and the policy implications of the study.

2. Literature Review and Contribution

This section surveys three strands of literature pertaining to the Granger-causal relationship between innovation, ICT penetration, and economic growth.[3] Additionally, in view of mixed results from past studies, this section discusses and highlights the specific contributions of this paper to the literature.

The first strand of the literature examines the link between innovation diffusion and economic growth. The Granger causality between the two can be addressed in four different ways. Firstly, the *supply-leading hypothesis* (SLH^{A}) of innovation-growth nexus, holds that innovation diffusion Granger causes economic growth. The supporters

[3] Table A.1 in Appendix A provides a brief summary of the past studies and their findings of the direction of Granger causality.

of the SLH^A are Adak (2015), Grossman and Helpman (1991), Guloglu and Tekin (2012), Kirchhoff et al. (2007), Fan (2011), and Pradhan et al. (2016c). Secondly, the *demand-following hypothesis* (*DF*H^A) of innovation-growth nexus, claims that economic growth Granger causes innovation diffusion. The supporters of the DFH^A are Howells (2005), Pradhan et al. (2016c), Sadraoui et al. (2014), and Sinha (2008). Thirdly, the *feedback hypothesis* (FBH^A) of innovation-growth nexus, suggests that both innovation and economic growth Granger cause each other. The proponents of the FBH^A are Galindo and Mendez (2014), Hasan and Tucci (2010), Howells (2005), and Pradhan et al. (2016c). Fourthly, the *neutrality hypothesis* (NEH^A) of innovation-growth nexus, holds that both innovation diffusion and economic growth do not Granger cause each other. The supporters of the NEH^A are Galindo and Mendez (2014), Hasan and Tucci (2010), Howells (2005), and Pradhan et al. (2016c). Interestingly, some studies offer mixed evidence. For instance, Pradhan et al. (2017a,b) and Pradhan et al. (2016c) support the validity of all these four hypotheses.

The second strand of the literature considers the connection between ICT penetration and economic growth.[4] Similar to the previous case, the Granger causality between these two variables can be addressed in four different ways. Firstly, the *supply-leading hypothesis* (SLH^B) of ICT-growth nexus, claims that ICT penetration Granger causes economic growth. The followers of the SLH^B are Mehmood and Siddiqui (2013), Ahmed and Krishnasamy (2012), Shiu and Lam (2008a), Yoo and Kwak (2004), Cieslik and Kaniewsk (2004), Chakraborty and Nandi (2003), Dutta (2001), and Roller and

[4] Studies in the literature use different terms to describe the evolution of ICT. Some refer to ICT infrastructure and use variables such as the number of internet servers and fixed broadband. Throughout the present study and for the sake of consistency, we refer to ICT penetration and use several different proxies to capture this variable. In the literature review in this section, we use the term 'penetration', but depending on the study being reviewed here, 'penetration' could mean infrastructure, development, or prevalence – terms that are used by different authors.

Waverman (2001). Secondly, the *demand-following hypothesis* (DFH^{B}) of ICT-growth nexus, suggests that economic growth Granger causes ICT penetration. The followers of the DFH^{B} are Pradhan et al. (2017a,b), Pradhan et al. (2014a), Pradhan et al. (2013a), Lee (2011), Veeramacheneni et al. (2007), and Beil et al. (2005). Thirdly, the *feedback hypothesis* (FBH^{B}) of ICT-growth nexus, claims that both ICT penetration and economic growth Granger cause each other. The proponents of the FBH^{B} are Pradhan et al. (2015), Pradhan et al. (2013b), Chakraborty and Nandi (2011, 2009), Lam and Shiu (2010), Ramlan and Ahmed (2009), Zahra et al. (2008), Shiu and Lam (2008b), Yoo and Kwak (2004), and Cronin et al. (1993a, b). Fourthly, the *neutrality hypothesis* (NEH^{B}) of ICT-growth nexus, posits that both ICT penetration and economic growth do not Granger cause each other. The supporters of the NEH^{B} are Pradhan et al. (2016a,b), Veeramacheneni et al. (2007), Shiu and Lam (2008b), and Dutta (2001). Interestingly, some studies offer mixed evidence. For instance, Pradhan et al. (2018, 2016a,b) support the validity of all these four hypotheses.

The third strand of the literature considers the nexus between ICT penetration and innovation. Similar to the previous two cases, the Granger causality between these two variables can be addressed in four different ways. These include the *supply-leading hypothesis* (SLH^{C}) of ICT-innovation nexus, where ICT penetration Granger causes innovation; the *demand-following hypothesis* (DFH^{C}) of ICT-innovation nexus, where innovation Granger causes ICT penetration; and the *feedback hypothesis* (FBH^{C}) of ICT-innovation nexus, where both ICT penetration and innovation diffusion Granger cause each other. Moreover, there is also the feasibility of no causal Granger relationship between ICT penetration and innovation diffusion, supporting a neutrality hypothesis (NLH^{C}). However, the literature on this specific topic is very scarce. A study that focuses on the relationship between ICT penetration and innovation are Pradhan et al. (2017b).

As noted above, while the relationships between economic growth, innovation diffusion, and ICT penetration have been well-studied, there is no real consensus on the causal direction of these relationships. Additionally, most studies on these relationships use a bivariate model and thus only consider two of these variables at any given time. The present study fills this gap by deploying a Granger causality approach to understand the dynamics between innovation diffusion,[5] ICT penetration, and economic growth on a broad scale for European countries[6] observed during the period 1961-2016. Our paper is related to the work of Pradhan et al. (2017b) which uses data on 32 high-income OECD countries. However, the present study expands the work of Pradhan et al. (2017b) by answering three critical questions in the context of European economies. Firstly, does economic growth stemming from innovation lead to further innovation? Secondly, does innovation emanating from economic growth lead to further economic growth? Thirdly, is it ICT penetration or economic growth that is the main driver of innovation in these countries?

The contributions of this study are three-fold. Firstly, the results of this study shed additional light on the *trivariate* causal relationship between ICT penetration, innovation diffusion, and per capita economic growth. By deploying a multivariate panel data

[5] It can be noted that diffusion modelling studies have tried to explain and analyse the patterns of diffusion of innovations, usually over time and across population of potential adopters, and thus, forecast diffusion of the innovation. The particular emphasis has been on predicting the ultimate level of penetration (see, for instance, Bagchi et al., 2008).

[6] The countries comprise Albania, Andorra, Armenia, Austria, Azerbaijan, Belarus, Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Hungary, Iceland, Ireland, Italy, Kazakhstan, Kosovo, Latvia, Liechtenstein, Lithuania, Luxembourg, Macedonia, Malta, Moldova, Monaco, Montenegro, the Netherlands, Norway, Poland, Portugal, Romania, the Russian Federation, San Marino, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, and the United Kingdom. As is evident, a few of these are transcontinental countries which span more than one continent. World Bank definitions are used.

estimation technique, the study offers more robust estimates by utilizing variations among countries as well as variations over time. Secondly, the present study considers European countries rather than high-income OECD countries that a recent study by Pradhan et al. (2017b) considers. Indeed, surprisingly, European countries as a group have received little attention in the existing literature. Thirdly, our data set (1960-2016) is more comprehensive compared to Pradhan et al. (2017b) who consider a shorter time period (1970-2016). We also entertain more proxies for innovation compared to Pradhan et al. (2017a,b) who focus on only four measures of innovation. Additionally, we utilize both individual indicators of ICT penetration, as well as its overall index.

In sum, one of the main contributions of the present paper is its inclusion of ICT penetration, which is an important covariate in examining the linkage between innovation diffusion and economic growth. Moreover, considering additional innovation diffusion indicators may not only alter the direction of Granger causal nexus of innovation diffusion – ICT penetration – economic growth, but also the magnitude of the estimates. It is therefore expected that the results of the present paper will not only add significantly to the existing body of knowledge, but the resultant detailed policy recommendations will contribute to the practical application of the results of this research paper.

3. Data and Methodology

We use annual time series data obtained from *World Development Indicators* of the World Bank for the selected European countries over the period 1961-2016.[7] The choice of this group of countries is two-fold. First, we chose this group due to the availability of

[7] We have an unbalanced panel since data on the variables is not uniformly available for all the countries and for all the years over the period of our investigation.

the data that is needed to undertake advanced panel data analysis for the variables we want to study (economic growth, ICT penetration, and innovation diffusion). It is challenging to obtain detailed data for some of the indicators, especially for the innovation indicators, for countries in other regions. Second, this is a remarkable group of countries that includes lower middle-income (e.g. Armenia and Moldova), upper middle-income (e.g. Belarus and Turkey) and high-income (e.g. Norway and Switzerland) countries. As such the countries are in different stages of economic development and constitute an interesting group of countries to study.

The present study deploys real per capita economic growth (PEG) and eight different indicators for innovation diffusion (INN), namely the number of patents by residents measured per thousand of population (PAR); the number of patents by non-residents measured per thousand of population (PAN); the number of patents by both residents and non-residents measured per thousand of population (PAT); research and development expenditure measured as a percentage of gross domestic product (RDE); researchers in research and development activities measured per thousand of population (RRD); high-technology exports measured as a percentage of gross domestic product (HTX); scientific and technical journal articles measured per thousand of population (STJ); and trademark applications measured per thousand of population (TRM). These proxies for innovation diffusion have previously been used, for example, by Galindo and Mendez (2014), Guloglu and Tekin (2012), Kaneva and Untura (2016), Kim and Lee (2015), Pradhan et al. (2016c, 2017a,b).

It should be noted that we have no direct variables that can represent the status of innovation diffusion in a country at a particular period of time. The inclusion of the eight indicators is intended to give a representative approximation for innovation diffusion, particularly with reference to examining the Granger-causal relationship between ICT penetration and per capita economic growth. Evidently, innovation diffusion indicators vary from study to study. For example, the study by Guloglu and Tekin (2012) places high importance on both patents (an output type innovation) and R & D expenditure (an input type innovation) for regulating the long-run economic growth in high-income OECD countries, while the study by Kaneva and Untura (2016) offers high importance to both research and development (R & D) expenditure and R & D staff (an input type innovation) for regulating long-run economic growth in the Russian Federation. Brenner (2014) places more emphasis on both scientific and technical publications (an output type innovation) and R & D expenditure for regulating the long-run economic growth in a group of developed and developing countries.

The present study uses various indicators as proxies for the ICT penetration. These indicators, all expressed per thousand of population, are telephone landlines (TEL), mobile phones (MOB), internet users (INU), internet servers (INS), and fixed broadband (FIB). These proxies for ICT penetration have previously been used, for example, by Majeed and Khan (2018), Pradhan et al. (2014b, 2017a,b), Zaman et al. (2012), Bayo-Moriones and Lera-Lopez (2007), and Cuervo and Menendez (2006). Appendix B provides a more detailed description of the variables (see Table B.1).

In addition, we construct[8] two composite indices, one for ICT penetration (CIC) and one for innovation diffusion (CII),[9] using principal component analysis (PCA). Appendix C provides additional information on the construction of these two indices (see Tables C.1 and C.2). The advantage of using these indices is that they can harness the richness

[8] The procedural details are discussed in Pradhan et al. (2014a,b).

[9] CIC is the weighted average of five ICT penetration indicators, namely, TEL, MOB, INU, INS and FIB. CII is the weighted average of seven innovation diffusion indicators, namely, PAR, PAN, RDE, RRD, HTX, STJ, and TRM. PAT is not included in the construction of CII to avoid double counting PAR and PAN.

of information and can capture multiple aspects of the subject at hand. We design these indices as per the OECD recommended procedures (see, for instance, OECD, 2008).

The present study considers nine different setups and six cases on the basis of nine indicators of innovation diffusion and six indicators of ICT penetration. The nine setups are based on different measures of innovation diffusion while the six cases are based on different measures ICT penetration.[10]

All the variables are converted into their natural logarithms for our estimation. Furthermore, all the monetary variables are expressed in constant US dollars. Table D.1 provides the descriptive statistics (mean, maximum, minimum, standard deviation, skewness and kurtosis) and the correlations (see Appendix D). The results of the correlation matrix indicate that the eight individual indicators of innovation (i.e., *PAR*, *PAN, PAT, RDE, RRD, HTX, STJ,* and *TRM*) and the five individual indicators of ICT penetration (i.e., *TEL, MOB, INU, INS,* and *FIB*) are highly correlated. Thus, the problem of multicollinearity would exist if these variables are used individually at the same time in one's empirical equation. This confirms our belief that only one variable at a time should be used in the analysis, meaning that the variables should not be used as separate covariates in our empirical model.

We estimate the dynamic panel regression of output on a number of customary growth determinants, particularly by the inclusion of different proxies of both ICT penetration and innovation diffusion. The estimated empirical models are given below.

[10] The subset of countries and the years covered under each of these set ups and cases are on the basis of data availability for the selected variables. We have an unbalanced panel in this study.

$$\Delta Innovation\,Diffusion_{it} = \kappa_{1j} + \lambda_{1i} ECT_{1t-1} + \sum_{k=1}^{p_1} \mu_{11ik} \Delta Innovation\,Diffusion_{it-k} +$$

$$\sum_{k=1}^{p_2} \mu_{12ik} \Delta ICT\;\;Penetration_{it-k} + \sum_{k=1}^{p_3} \mu_{13ik} \Delta Per\;Capita\;Economic\;Growth_{it-k} + \varepsilon_{1it}$$

(1)

H_0: μ_{12ik} = 0; μ_{13ik} = 0; and λ_{1i} = 0 for k = 1,..., P_1 - P_3

H_A: $\mu_{12ik} \neq 0$; $\mu_{13ik} \neq 0$; and $\lambda_{1i} \neq 0$ for at least one k

$$\Delta ICT\;\;Penetration_{it} = \kappa_{2j} + \lambda_{2i} ECT_{2t-1} + \sum_{k=1}^{p_1} \mu_{21ik} \Delta ICT\;\;Penetration_{it-k} +$$

$$\sum_{k=1}^{p_2} \mu_{22ik} \Delta Innovation\,Diffusion_{it-k} + \sum_{k=1}^{p_3} \mu_{23ik} \Delta Per\;Capita\;Economic\;Growth_{it-k} + \varepsilon_{2it}$$

(2)

H_0: μ_{22ik} = 0; μ_{23ik} = 0; and λ_{2i} = 0 for k = 1,..., P_1 - P_3

H_A: $\mu_{22ik} \neq 0$; $\mu_{23ik} \neq 0$; and $\lambda_{2i} \neq 0$ for at least one k

$$\Delta Per\;Capita\;Economic\;Growth_{it} = \kappa_{3j} + \lambda_{3i} ECT_{3t-1} +$$

$$\sum_{k=1}^{p_1} \mu_{31ik} \Delta Per\;Capita\;Economic\;Growth_{it-k} + \sum_{k=1}^{p_2} \mu_{32ik} \Delta ICT\;\;Penetration_{it-k} +$$

$$\sum_{k=1}^{p_3} \mu_{33ik} \Delta Innovation\,Diffusion_{it-k} + \varepsilon_{3it}$$

(3)

H_0: μ_{32ik} = 0; μ_{33ik} = 0; and λ_{3i} = 0 for k = 1,..., P_1 - P_3

H_A: $\mu_{32ik} \neq 0$; $\mu_{33ik} \neq 0$; and $\lambda_{3i} \neq 0$ for at least one k

where Δ is the first difference operator, *i* is country and *t* is year in the panel, and *ε* is the error term. *Innovation diffusion* (INN) is defined as PAR, PAN, PAT, RDE, RRD, HTX, STJ, TRM, or CII; and *ICT penetration* (ICT) is defined as TEL, MOB, INU, INS, FIB, or CIC.

The ECT_{t-1}'s are the lagged error-correction terms that capture the long-run dynamics, while the differenced variables represent the short-run dynamics among innovation diffusion, ICT penetration, and per capita economic growth. The above vector error-correction model (VECM) provides robust results if the deployed variables are integrated of order one and cointegrated. If the variables used in equations 1 to 3 are not cointegrated, the ECT_{t-1}'s are removed in the empirical investigation process. Several possibilities exist here. For example, if neither μ_{12ik}, μ_{13ik}, μ_{22ik}, μ_{23ik}, μ_{32ik}, nor μ_{33ik} are significantly different from zero, innovation diffusion, ICT penetration, and per capita economic growth are not causally interrelated. On the contrary, if all μ_{12ik}, μ_{13ik}, μ_{22ik}, μ_{23ik}, μ_{32ik}, and μ_{33ik} are significantly different from zero, there is causality among the variables. Figure 1 presents a synopsis of the hypotheses that are tested in this empirical investigation.

<<Insert Figure 1 here>>

It should be noted that the choice of lag lengths is crucial in the VECM estimation, as causality test results may depend critically on the choice of a suitable lag structure. In this study, we use the Akaike Information Criterion (AIC) to determine the optimum lag lengths. The AIC is widely accepted in the literature as a means of choosing lags optimally.

4. Empirical Results

The VECM framework is used to examine the possible Granger causal relationships among innovation diffusion, ICT penetration, and per capita economic growth. The first step of this framework is to determine the order of integration and presence/absence of cointegration[11] among the three sets of variables.

[11] Cointegration entails a long-run equilibrium relationship that ties the three time-series variables even though short-term departures from equilibrium may exist (see Engle and Granger, 1987 for an explanation).

We use the Breitung unit root test to identify the order of integration of the variables in our panel setting. The test verifies that all the variables are integrated of order one (see Appendix Table D.1, Part A). These results suggest the likelihood of cointegration among innovation diffusion, ICT penetration, and per capita economic growth. The Johansen panel cointegration test (Larsson et al., 2001) is then used to test the hypothesis that there is a long-run relationship among these three sets of variables (see Table 1). The results from this test validate the existence of a long-run equilibrium relationship among innovation diffusion, ICT penetration, and per capita economic growth in our nine setups and six cases of each setup.

<<Insert Table 1 here>>

The above findings support the deployment of the VECM method to observe the Granger causal relationship among innovation diffusion, ICT penetration, and per capita economic growth. The results of this section are presented in Table 2.

<<Insert Table 2 here>>

We first analyse the long-run Granger causality results, established by examining the statistical significance of the ECT_{-1} coefficients. We find that when ΔPEG is the dependent variable, the coefficients for ECT terms are statistically significant at 1 to 5% levels. This implies that per capita economic growth converges to its long-run equilibrium path in response to changes in both ICT penetration and innovation diffusion. This is true for all the cases that we consider (see Table 2). Subsequently, the deduction is that per capita economic growth in European countries is significantly influenced by both innovation diffusion and ICT penetration. The implication of this finding is that to stimulate long-run economic growth, it is imperative to facilitate both innovation diffusion and ICT penetration in the European countries. In other words, we find support for the supply-leading hypothesis with respect to the interaction between innovation diffusion and economic growth and with respect to the link between ICT penetration and economic growth.

As a test for robustness, we have also deployed mixed effects generalized linear model (GLM) estimation to better understand the impact of innovation diffusion and ICT penetration on economic growth. Table E.1 in Appendix E presents the results of these estimations. We have analysed the same nine setups and six cases that we used with the VECM model. The results clearly indicate that both innovation and ICT penetration have substantial and significant impacts on economic growth.

In addition to the consistent finding (across all setups and cases) that both ICT penetration and innovation diffusion Granger-cause per capita economic growth in the long run, there are other long-run results that apply to specific cases or setups. The empirical findings also show that for Setups 1, 2 and 3 (Case 2) and Setup 5 (Case 2), the coefficients for the lagged ECT terms for the dependent variable ΔICT are statistically significant at a 5% level. This suggests that mobile phone penetration converges to its long-run path in response to changes in innovation (measured by PAR, PAN, PAT, or RRD) and economic growth. The implication of this result is that the long-run path of mobile penetration rates is influenced by innovation diffusion (specifically patents and researchers in R&D activities) and economic growth in Europe. This result is not surprising, as patent activities in the ICT sector have been on an upward trend and ICT firms tend to generate more patents than non-ICT firms (Lantz et al. 2011). New user-friendly mobile applications and services across the globe have had a positive impact on the mobile phone and other ICT penetration rates.

The results also indicate that for Setup 6 (Case 1), the coefficient for the lagged ECT term for the dependent variable ΔHTX is statistically significant at the 5% level. This suggests that the long-run path of innovation, as measured by high-tech exports, is influenced by economic growth rates and the ICT penetration rate. This result indicates that wealthier and more technologically connected economies in the EU are also the ones with stronger high-technology exports.

While the long-run results are mostly uniform, the short-run results are mostly non-uniform, with only a few exceptions. The uniform finding is a bidirectional causality which exists between ICT penetration (for Case 6) and economic growth[12] [see Table 3]. Furthermore, out of 54 instances, there are 44 instances that find bidirectional causality between ICT penetration and economic growth in the short run. A summary of the non-uniform short-run Granger causality results is provided in Table 3 and demonstrates that the short-run adjustment dynamics vary across the nine setups and six cases[13].

<<Insert Table 3 here>>

Some additional estimation and results, though not described in detail, warrant a brief note. Firstly, we procured FMOLS[14] and DOLS[15] estimates. These show that both innovation diffusion and ICT penetration have positive impacts on per capita economic

[12] This result supports the findings of Pradhan et al. (2014a, 2016a,b).

[13] In the case of the short-run relationship between innovation diffusion and economic growth, there are 15 instances supporting the supply-leading hypothesis, 10 instances supporting the demand-following hypothesis, 22 instances supporting the feedback hypothesis, and 7 instances supporting the neutrality hypothesis. In the case of the short-run relationship between ICT penetration and economic growth, there are 5 instances supporting the supply-leading hypothesis, 5 instances supporting the demand-following hypothesis, 44 instances supporting the feedback hypothesis, and 0 instances supporting the neutrality hypothesis.

[14] FMOLS is fully modified ordinary least squares (OLS), a non-parametric estimation approach, taking into account the possible correlation between the error term and the first differences of regressor as well as the presence of a constant term to deal with corrections for serial correlation (Pedroni, 2000).

[15] DOLS is dynamic OLS, a parametric estimation approach that adjusts the errors by augmenting the static regression with leads, lags, and contemporaneous values of the regressor in first differences (Kao and Chiang, 2000).

growth congruent with the findings of Jin and Cho (2015) and Bayo-Moriones and Lera-Lopez, 2007. These results are not reported in the text due to space constraints and are available from the authors on request.

Secondly, we conducted sensitivity analysis by changing the order of the VECM. There were no significant changes to the earlier results reported in Tables 2 and 3.

Thirdly, we utilized generalized impulse response functions (GIRFs) to trace the effect of a one-off shock to one of the inventions on the current and future values of the endogenous variables. The GIRFs offered additional insight into how shocks to per capita economic growth can affect and be affected by both innovation diffusion and ICT penetration. The results from GIRF estimations are not reported here due to space constraints and can be made available on request. This analysis provides additional sustenance for the argument that there is causality among innovation diffusion, ICT penetration, and per capita economic growth, as outlined above for nine setups and six cases in each setup of the present study.

5. Discussion, Conclusion, and Policy Implications

The study aims to examine causal relationships among innovation diffusion, ICT penetration, and per capita economic growth in selected European countries over the period 1961-2016. These countries include lower middle-, upper middle-, and high-income nations. Due to varying levels of economic development among countries, the study endeavors to identify two possible key drivers for economic growth and the type of co-development policies that help laggard economies catch-up with more successful ones in the continent.

We find that our three variables (innovation, ICT penetration, and economic growth) are integrated of order one and cointegrated, regardless of the particular innovation diffusion indicators and ICT penetration indicators that we consider. In addition, there is clear evidence that both innovation diffusion and ICT penetration matter in the determination of long-run per capita economic growth. There is also evidence to suggest that for some measures of innovation (patents filed by residents & non-residents, total patents filed, and researchers involved in R&D activities), both economic growth and innovation contribute to increased mobile-phone adoption in the long run. The empirical analysis also shows that broad-based ICT penetration (CIC) and economic growth have a long-term impact on innovation (patents filed by residents). Moreover, results suggest that telephone adoption and economic growth have a long-run impact on total patents filed in the countries, patents filed by residents, and high-tech exports. These results have been observed based on cointegration and vector error-correction modelling and further verified through mixed effects modelling. Interestingly, we do not tend to find unique results in the short run. Perhaps the most consistent result in the short run is the feedback relationship between ICT penetration and economic growth in approximately 80% of the results.

In the case of our short-run results, in some situations the effect is bidirectional, while it is unidirectional (either direction) in other situations, depending upon the types of innovation diffusion and ICT penetration we incorporate in the estimation process. In particular, we expected to find bidirectional causality between ICT penetration and growth, between innovation and growth, and between ICT penetration and innovation in European countries. Although bidirectional causality does not uniformly exist, it exists in several instances (cases/setups), particularly with respect to high technology exports and the composite index of innovation when considering the relationship between innovation and economic growth, and with respect to scientific and technology articles and the composite index of innovation when considering the relationship between innovation diffusion and ICT penetration.

The results above show that the impacts of ICT penetration, innovation diffusion, and economic growth often reinforce and deepen one another – all of which are critical for the sustained economic performance of European countries. Evidently, the mixture of bidirectional and unidirectional causality results for the short-run and long-run dynamics show that there are strong inter-linkages between these variables. Hence, there is need to develop favourable policies to elevate the ICT infrastructure and innovation diffusion in order to generate more sustainable economic growth in European countries in both the short and long run. Similarly, sustainable per capita economic growth in these countries is likely to generate more pronounced investment opportunities to enhance both innovation diffusion and ICT penetration in the short run.

On the basis of the results and discussions, this study carries the following policy implications:

With regard to the ICT penetration - economic growth nexus: The digital economy is increasingly becoming an important driver for economic agents to enhance their reach for resources and markets. ICT penetration is also an important enabler for economic agents to enhance the richness of their products and services. In this context, ICT penetration is not only a major revenue earner as an industry, but also an important enabler for other sectors of the economy to become productive and competitive. Hence, ICT penetration enables economic agents to pursue both economies of scale and scope.

To promote economic growth, a clear and systematic digital plan must be in place within Europe to provide high-quality ICT infrastructure and high-speed ICT services. The rollout of high-quality ICT infrastructure and services are more critical in the less developed regions of Europe, where bridging the digital-divide would also close the knowledge-divide and income-divide across the regions. Access to sound digital platforms would assist rural and remote communities and SMEs in Europe transcend geographical limitations and rigidities to access opportunities from the more developed and wealthy regions of Europe. In this context, the government should provide adequate support to build infrastructure and expand ICT penetration. Countries without a sound ICT infrastructure policy will not be able to sustain viable ICT penetration. This may hinder the economic development process and innovations that contribute to economic growth. Conversely, economic growth is likely to lead to further ICT infrastructure development and ICT penetration. Increasing income levels will increase demand for more sophisticated technology from consumers and firms since technology is a normal commodity.

With regard to the innovation -economic growth nexus: In order to stimulate economic growth, attention must be paid to policies that promote innovation. This includes strengthening the national innovation ecosystem, which entails undertaking the following actions:

- providing adequate financial and tax incentives to support basic and translational R&D, the development of new startups, patent filing and trademarks, and the creation of a vibrant venture capital industry;
- putting in place a sound regulatory framework and institutional architecture that support and protect intellectual property, including streamlining the patent application process, and reducing 'red-tape' that lengthens the time period for registering the patents;
- educating researchers and industry on the generation of intellectual property (IP) and putting in place effective enforcement mechanism for violation IP rights;

- increasing the number of R&D personnel with sound multidisciplinary skills, including a good understanding of business development and entrepreneurship;
- increasing the supply of talent in the science, technology, engineering mathematics (STEM) related areas with strong research skills, which includes providing generous scholarships and other support to encourage enrolments in STEM-related undergraduate and postgraduate research programs; and
- promoting the development of industrial clusters and technology parks that would create a vibrant high-technology sector.

With regard to the ICT penetration - innovation diffusion nexus: In order to facilitate better innovation, a greater degree of ICT penetration is desirable in these European countries. Creation of a well-developed ICT infrastructure, both hardware and software, can facilitate further investment and an easier means of creating an environment to support the activities of innovation which will inevitably lead to better outcomes for the economy. These include incorporating Industry 4.0 framework (also known as Industrial Internet or Digital Factory) for all the industrial sectors. Industry 4.0 includes incorporating cyber-physical systems, the internet of things, cloud computing, data analytic tools and cognitive computing to create M2M (Machine-to-Machine) automation and learning systems (MacDougall, 2014). M2M systems enable firms to manage the entire industrial floor and firms' operations with minimal human supervision. Continuous development and integration of new intelligent systems within the industrial sectors will not only enhance the productivity of the existing sectors, but also spawn new industries that contribute to economic growth. In this vein, a study by Geissbauer et al. (2016) shows that global firms[16] will invest close to USD 907 million per annum in ICT, generating revenue of USD 493 billion per annum from these technologies, and obtaining cost efficiency gains of USD 421 billion per annum from 2016 to 2020.

In summary, the above discussions show that economic growth can be enhanced if European countries develop a strong national innovation ecosystem underpinned by sound ICT policies and strategies. To sustain their economic wealth in a highly globalized and competitive environment, European economies will be required to continue investing in innovation and increasing the use of the digital platforms among the various economic agents. Evidently, our findings highlight that policy-makers should give priority to co-development policies pertaining to innovation, ICT penetration, and economic growth stimulating initiatives – to ensure that these policies reinforce one another.

In all, this paper fills a gap in the literature by furthering the understanding of the economic growth–innovation–ICT nexus through utilizing many indicators for both innovation and ICT. We considered a long span of time for European countries which are in different states of economic development. Moreover, the use of two composite indices in our empirical investigation added a noteworthy contribution to the literature, compared to the previous studies.

The key findings of our study point to an important final word, namely that policies pertaining to innovation, ICT penetration, and economic growth cannot be formulated in

[16] This is based on a worldwide survey of firms in nine major industrial sectors from several countries across Europe, the Americas, Asia Pacific, Middle East and Africa. The industries that are expected to experience the highest cost reductions are: Aerospace, Defense and Security; Automotive; Chemicals; Electronics; Engineering and Construction; Forest, Paper & Packaging; Industrial Manufacturing; Metals; and Transportation and Logistics. The countries included in the survey were Australia, Austria, Brazil, Canada, China, Denmark, Finland, France, Germany, India, Italy, Japan, Mexico, Middle East, Netherlands, Poland, Portugal, Singapore, South Africa, Spain, Sweden, Switzerland, the United Kingdom and the United States.

isolation. Careful orchestration of the policies is required to ensure that the economic ecosystems in Europe can harness the inter-linkages between these key variables and enhance the multiplier-effect within the economies. While a possible multiplier-effect has been mentioned in the literature, our study provides robust empirical evidence to support this postulation by studying the inter-linkages between the three variables for the case of Europe. These inter-linkages are becoming important in an increasingly hyper-converged global economy powered by innovation in ICT. Clearly, our findings may be a useful case study for countries in other regions which may be interested in developing more resilient and dynamic economic ecosystems.

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Appendix A: Literature Review

Table A. 1. Nexus between Innovation Diffusion, ICT Penetration, and Economic Growth

Study	Variables used for INN, ICT, PEG	Coverage	Time Period	Major Finding(s)
Part I: Between Innovation Diffusion and Economic Growth				
Pradhan et al. (2017a)	A1-A5	OECD Countries	1970-2016	SLH^{A}, DFH^{A}, FBH^{A}
Pradhan et al. (2016a)	A1-A6	Eurozone countries	1961-2013	SLH^{A}, DFH^{A}, FBH^{A}, NEH^{A}
Cetin (2013)	A4	9 European countries	1981-2008	SLH^{A}, DFH^{A}, FBH^{A}, NEH^{A}
Guloglu and Tekin (2012)	A3-A4	13 OECD countries	1991-2007	SLH^{A}, DFH^{A}, FBH^{A}
Hasan and Tucci (2010)	A3-A4	58 countries	1980-2003	FBH^{A}
Agenor and Neanidis (2015)	A3	38 countries	1981-2008	SLH^{A}
Sadraoui et al. (2014)	A4	32 countries	1970-2012	FBH^{A}
Galindo and Mendez (2014)	A3	13 developed countries	2002-2007	FBH^{A}
Kirchhoff et al. (2012)	A4	USA	1990-1989	SLH^{A}, DFH^{A}, FBH^{A}, NEH^{A}
Yang (2006)	A3	Taiwan	1951-2001	SLH^{A}
Part II: Between ICT Penetration and Economic Growth				
Pradhan et al. (2017a)	B6	OECD Countries	1970-2016	SLH^{B}
Pradhan et al. (2017b)	B1-B6	21 Asian Countries	2001-2012	SLH^{B}, DFH^{B}, FBH^{B}
Pradhan et al. (2015)	B1-B6	21 Asian Countries	2001-2012	SLH^{B}, DFH^{B}, FBH^{B}
Shahiduzzaman and Alam (2014)	B7	Australia	1965-2011	SLH^{B}
Arvin and Pradhan (2014)	B5	G-20 countries	1998-2011	FBH^{B}
Chakraborty and Nandi (2003)	B1	12 Asian Countries	1975-2000	SLH^{B}
Chakraborty and Nandi (2009)	B1	DCs	1980-2001	FBH^{B}
Chakraborty and Nandi (2011)	B1	93 countries	1985-2007	FBH^{B}
Cieslik and Kaniewsk (2004)	B1	Poland	1989-1998	SLH^{B}
Cronin et al. (1991)	B1	USA	1958-1988	FBH^{B}
Dutta (2001)	B1, B2	15 DCs & 15 ICs	1960-1993	SLH^{B}
Ghosh and Prasad (2012)	B1	India	1980-2006	SLH^{B}
Hagshenas et al. (2013)	B1, B2	Iran	1975-2009	FBH^{B}
Lam and Shiu (2010)	B2	105 countries	1980-2006	FBH^{B}
Lee et al. (2012)	B1	3 NACs	1975-2009	DFH^{B}
Mehmood and Siddiqui (2013)	B2	23 Asian Countries	1990-2010	SLH^{B}
Pradhan et al. (2013b)	B3	34 OECD countries	1961-2011	DFH^{B}, FBH^{B}
Ramlan and Ahmed (2009)	B1	Malaysia	1965-2005	NLH^{B}
Shiu and Lam (2008a)	B1	China	1978-2004	SLH^{B}, DFH^{B}, NLH^{B}
Shiu and Lam (2008b)	B1	105 countries	1980-2006	FBH^{B}
Yoo and Kwak (2004)	B1	Korea	1965-1998	SLH^{B}
Zahra et al. (2008)	B1	23 countries	1990-2007	FBH^{B}

Part III: Between ICT Penetration and Innovation Diffusion				
Pradhan et al. (2017a)	A1-A5; B6	OECD Countries	1970-2016	SLH^{C}, DFH^{C}, NEH^{C}
Lee et al. (2016)	A1, B5	40 countries	1999-2013	SLH^{C}

Note 1**:** SLH^{A}: Supply-leading hypothesis: unidirectional causality from innovation diffusion to economic growth; DFH^{A}: Demand-following hypothesis: unidirectional causality from economic growth to innovation diffusion; FBH^{A}: Feedback hypothesis: bidirectional causality between innovation diffusion and economic growth; and NLH^{A}: Neutrality hypothesis: no causality between innovation diffusion and economic growth.

Note 2: SLH^{B}: Supply-leading hypothesis: unidirectional causality from ICT penetration to economic growth; DFH^{B}: Demand-following hypothesis: unidirectional causality from economic growth to ICT penetration; FBH^{B}: Feedback hypothesis: bidirectional causality between ICT penetration and economic growth; and NLH^{B}: Neutrality hypothesis: no causality between ICT penetration and economic growth.

Note 3**:** SLH^{c}: Supply-leading hypothesis: unidirectional causality from ICT penetration to innovation; DFH^{c}: Demand-following hypothesis: unidirectional causality from innovation diffusion to ICT penetration; FBH^{c}: Feedback hypothesis: bidirectional causality between ICT penetration and innovation diffusion; and NLH^{c}: Neutrality hypothesis: if no causality between ICT penetration and innovation diffusion.

Note 4**:** A1 is patents residents, A2 is patent non-residents, A3 is patents filled by both residents and non-residents, A4 is research and development expenditure, A5 is researchers in research and development activities, A6 is composite index of innovation, B1 is telephone mainlines, B2 is mobile phones, B3 is internet users, B4 is internet servers, B5 is fixed broadband, and B6 is composite index of ICT penetration.

Note 5: OECD is the organization for economic cooperation and development, EEA is the European Economic Area countries, EU is the European Union, DCs: Developing Countries; NACs: Non-aligned Countries, and ICs: Industrialized Countries.

Note 6**:** ICT penetration does not have a uniform definition in the studies. It is captured by telephone mainlines, mobile phones, internet users, internet servers, or fixed broadband, depending on the study.

Note 7**:** Innovation diffusion is captured by patents, R&D expenditure, researchers in R&D activities, high technology exports, scientific and technical journal articles, or trademarks, depending on the study.

Appendix B: Variables

Table B.1. Definition of Variables

Variable Acronym	Variable Definition
SET 1: INNOVATION DIFFUSION INDICATORS	
PAR	**Patents filed by residents:** expressed in numbers per thousand population.
PAN	**Patents filed by non-residents:** expressed in numbers per thousand population.
PAT	**Patents total filed by both residents and non-residents:** expressed in numbers per thousand population.
RDE	**Research and development expenditure:** expressed as a percentage of gross domestic product.
RRD	**Researchers in research and development activities:** expressed in numbers per thousand population.
HTX	**High-technology exports:** expressed a percentage of gross domestic product.
STJ	**Scientific and technical journal articles:** expressed in numbers per thousand population.
TRM	**Trademark applications:** expressed in numbers per thousand population.
CII	**Composite index of innovation diffusion:** a composite index using PAR, PAN, RDE, RRD, HTX, STJ, and TRM – derived through principal component analysis (see Appendix C).
SET 2: ICT PENETRATION INDICATORS	
TEL	**Telephone landlines:** telephone landlines per thousand of population.
MOB	**Mobile phones:** mobile phone subscribers per thousand of population.
INU	**Internet users:** internet users per thousand of population.
INS	**Internet servers:** internet servers per thousand of population.
FIB	**Fixed broadband:** Fixed broadband per thousand of population.
CIC	**Composite index of ICT penetration:** a composite index using TEL, MOB, INU, INS, and FIB– derived through principal component analysis (see Appendix C).
SET 3: ECONOMIC GROWTH INDICATOR	
PEG	**Per capita economic growth:** defined as the percentage change in real per capita gross domestic product.

Note 1: ICT is information and communication technology.
Note 2: Variables above are defined more completely in the *World Development Indicators* of the World Bank.
Note 3: PAT is not included in the construction of CII to avoid double counting PAR and PAN.

Appendix C: Formulation of Composite Indices of Innovation Diffusion and ICT Penetration, Using Principal Component Analysis

The study forms two composite indices for innovation diffusion and ICT penetration, henceforth denoted by ‘CII’ and ‘CIC’, respectively. These two indices are constructed through principal component analysis (PCA) using the various indicators for innovation diffusion and ICT penetration (see Appendix B). Three key steps are followed: (1) data are organized in the same order to create an input matrix for the principal components; (2) using PCA, eigenvalues, factor loadings, and principal components are derived; and (3) the principal components are used to construct CII and CIC for each country for every year. This method is well described in many econometric textbooks and numerous research papers. Hence, these are not discussed here. Tables C.1 and C.2 present the statistical values from our principal component analysis.

Table C.1: Summary of PCA-related Information for our Innovation Diffusion Index (CII)

Part A: Eigen Analysis of Correlation Matrix

PCs	Eigen Value	Proportion Variance	Cumulative Percentage
1	2.771	0.396	0.396
2	2.073	0.296	0.692
3	0.918	0.131	0.823
4	0.634	0.091	0.914
5	0.379	0.054	0.968
6	0.118	0.017	0.985
7	0.107	0.015	1.000

Part B: Eigen Vectors (component loadings)

Variables	PC1	PC2	PC3	PC4	PC5	PC6	PC7
PAR	0.387	-0.390	-0.137	0.408	0.581	-0.082	0.411
PAN	0.321	0.372	-0.001	0.743	-0.451	0.039	-0.041
RDE	0.501	-0.321	-0.145	-0.081	0.033	0.036	-0.785
RRD	0.394	0.459	0.062	-0.271	0.261	0.688	0.123
HTX	0.130	-0.211	0.968	0.039	-0.017	0.003	-0.013
STJ	0.435	-0.327	-0.120	-0.363	-0.600	-0.015	0.445
TRM	0.367	0.494	0.075	-0.262	0.173	-0.719	0.020

Note 1: PCs denotes principal components.

Note 2: PAR is patents by residents, PAN is patent by non-residents, RDE is research and development expenditure, RRD is researchers in research and development activities, HTX is high-technology exports, STJ is scientific and technical articles, and TRM is trademark applications.

Note 3: Patents filled by both residents and non-residents (PAT) is not used in the formulation of the index since it is the sum of both PAR and PAN. In other words, to avoid double counting PAR and PAN, we exclude PAT in calculating CII.

Table C.2: Summary of PCA-related Information for our ICT Penetration Index (CIC)

Part A: Eigen Analysis of Correlation Matrix

PCs	Eigen Value	Proportion Variance	Cumulative Percentage
1	2.869	0.574	0.574
2	1.140	0.228	0.802
3	0.586	0.117	0.919
4	0.302	0.060	0.979
5	0.104	0.021	1.000

Part B: Eigen Vectors (component loadings)

Variables	PC1	PC2	PC3	PC4	PC5
TEL	0.296	-0.661	0.615	-0.311	0.024
MOB	0.329	0.688	0.290	-0.578	-0.027
INU	0.547	0.131	0.096	0.484	0.663
INS	0.437	-0.269	-0.727	-0.441	0.120
FIB	0.560	0.027	-0.022	0.375	-0.738

Note 1: PCs denotes principal components.

Note 2: TEL is telephone land lines, MOB is mobile phones, INU is internet users, INS is internet servers, and FIB is fixed broadband.

Appendix D: Statistics and Correlation Matrix

Table D.1. Descriptive Statistics, Unit Root Statistics, and Correlation Matrix

Part A: Descriptive Statistics and Unit Root Statistics

Variable	**Descriptive Statistics**						**Unit Root Statistics**		
	Mea	**Max**	**Min**	**StD**	**Ske**	**Kur**	**LD**	**FD**	**Inference**
PAR	-1.10	-0.22	-3.26	0.48	-0.60	3.90	3.759	-16.75	I [1]
PAN	-1.72	0.41	-3.32	0.67	0.52	3.07	0.002	-13.34	I [1]
PAT	-0.93	0.44	-2.58	0.48	0.04	3.03	0.006	-14.94	I [1]
RDE	0.01	0.59	-1.79	0.36	-1.21	6.84	2.571	-10.80	I [1]
RRD	-0.62	1.42	-2.26	0.71	0.19	2.97	3.678	-8.694	I [1]
HTX	0.254	1.27	-1.26	0.50	-0.26	2.53	0.175	-14.46	I [1]
STJ	-0.24	0.41	-1.87	0.45	-1.30	4.55	-2.759	-9.262	I [1]
TRM	0.14	1.19	-0.62	0.30	0.57	4.35	2.652	-17.39*	I [1]
CII	0.21	0.84	-1.01	0.33	-0.47	2.98	9.400	-6.219*	I [1]
TEL	2.56	2.86	2.14	0.16	-0.14	2.09	32.70	-10.37*	I [1]
MOB	2.99	3.27	2.12	0.16	-2.05	9.25	18.90	-2.496*	I [1]
INU	2.68	2.98	1.60	0.26	-1.64	6.10	15.74	-5.789*	I [1]
INS	-0.97	0.48	-2.99	0.78	-0.41	2.50	8.380	-7.010*	I [1]
FIB	1.97	2.61	-0.78	0.64	-1.94	6.89	10.67	4.6210*	I [1]
CIC	0.44	0.78	-0.33	0.21	-0.97	3.86	57.16	48.410*	I [1]
PEG	1.68	1.77	1.49	0.04	-1.14	6.29	-18.93	-31.00*	I [1]

Part B: Correlation Matrix

Variables	**PEG**	**PAR**	**PAN**	**RDE**	**RRD**	**HTE**	**STJ**	**TRM**	**TEL**	**MOB**	**INU**	**INS**	**FIB**
PEG	1.00	0.12	0.07	0.25*	0.07	0.07	0.33*	0.07	0.20*	0.26*	0.31*	0.37*	0.40*
PAR		1.00	0.49*	0.69*	0.07	0.38*	0.49*	-0.11	0.45*	0.19*	0.37*	0.40*	0.27*
PAN			1.00	0.34*	0.14**	0.18*	0.22*	0.20*	0.43*	-0.07	0.11	0.18**	-0.10
RDE				1.00	0.33*	0.52*	0.81*	0.14**	0.55*	0.35*	0.57*	0.67*	0.49*
RRD					1.00	0.33*	0.42*	0.75*	0.27*	0.18**	0.48*	0.54*	0.30*
HTX						1.00	0.51*	0.04	0.28*	0.27*	0.42*	0.46*	0.34*
STJ							1.00	0.21*	0.52*	0.46*	0.74*	0.82*	0.61*
TRM								1.00	0.29*	-0.07	0.25*	0.29*	0.11
TEL									1.00	0.05	0.33*	0.46*	0.23*
MOB										1.00	0.67*	0.52*	0.81*
INU											1.00	0.85*	0.86*
INS												1.00	0.75*
FIB													1.00

Note 1: PEG is per capita economic growth, PAR is patents by residents, PAN is patent by non-residents, PAT is patents filled by both residents and non-residents, RDE is research and development expenditure, RRD is researchers in research and development activities, HTX is high-technology exports, STJ is scientific and technical articles, TRM is trademark applications, CII is the composite index of innovation diffusion, TEL is telephone land lines, MOB is mobile phones, INU is internet users, INS is internet servers, FIB is fixed broadband, and CIC is the composite index of ICT penetration. Descriptive statistics are in natural logs. Natural logs are used in our estimation. All the monetary variables are expressed in constant US dollars.

Note 2: Mea is mean, Max is maximum, Min is minimum, Std is standard deviation, Ske is skewness, Kur is Kurtosis, LD is level data, FD is first difference data, and I [1] denotes integration of order one.

Note 3: * and ** indicate that parameter estimates are significant at the 1% and 5% levels, respectively.

Note 4: To save space, PAT is not included in the correlation matrix above given that it comprises PAR and PAN. Its inclusion would have been superfluous.

Appendix E: Mixed Effects Generalized Linear Model (GLM) Estimation

Table E.1. Results of Mixed Effects GLM Estimation

Set Ups	IVs	Dependent Variable: PEG					
		Case 1: TEL	**Case 2: MOB**	**Case 3: INU**	**Case 4: INS**	**Case 5: FIB**	**Case 6: CIC**
1: PAR	**INN**	0.011*	0.019*	0.009*	0.008*	0.013*	0.011*
	ICT	0.001*	0.004*	0.003*	0.012*	0.003*	0.006*
	Constant	1.671	1.667	1.667	1.668	1.669	1.671
	Wald χ^2	56.21*	77.98*	66.80*	112.6*	62.3*	65.26*
2: PAN	**INN**	0.005*	0.001*	0.002*	0.003*	0.007*	0.004*
	ICT	0.001*	0.005*	0.004*	0.014*	0.004*	0.006*
	Constant	1.671	1.671	1.672	1.672	1.673	1.673
	Wald χ^2	19.91*	49.18*	33.67*	86.9*	27.7*	27.2*
3: PAT	**INN**	0.008*	0.003*	0.005*	0.002*	0.109*	0.007*
	ICT	0.001*	0.005*	0.004*	0.014*	0.003*	0.006*
	Constant	1.671	1.670	1.671	1.672	1.673	1.674
	Wald χ^2	23.39*	51.56*	37.35*	88.18*	28.5*	32.25*
4: RDE	**INN**	0.035*	0.034*	0.036*	0.019*	0.036*	0.038*
	ICT	0.002*	0.005*	0.005*	0.012*	0.001*	0.009*
	Constant	1.671	1.670	1.671	1.673	1.675	1.677
	Wald χ^2	54.03*	92.15*	80.15*	97.9*	46.89*	70.05*
5: RRD	**INN**	0.005*	0.0001*	0.001*	0.003*	0.007*	0.004*
	ICT	0.002*	0.005*	0.005*	0.015*	0.001*	0.007*
	Constant	1.672	1.671	1.672	1.673	1.676	1.676
	Wald χ^2	11.51*	48.99*	31.69*	87.92*	18.43**	18.89*
6: HTX	**INN**	0.004*	0.006*	0.006*	0.002*	0.003*	0.006*
	ICT	0.003*	0.006*	0.005*	0.015*	0.001**	0.009*
	Constant	1.672	1.671	1.672	1.672	1.676	1.678
	Wald χ^2	19.49*	54.47*	37.49*	87.63*	11.61**	19.68*
7: STJ	**INN**	0.001*	0.001*	0.002*	0.002*	0.002*	0.004*
	ICT	0.002*	0.005*	0.005*	0.015*	0.004**	0.009*
	Constant	1.672	1.671	1.671	1.673	1.676	1.676
	Wald χ^2	17.67*	49.13*	32.61*	88.7*	11.51**	19.22*

8: TRM	**INN**	0.005*	0.001*	0.003*	0.006*	0.007*	0.004*
	ICT	0.002*	0.005*	0.004*	0.015*	0.002*	0.007*
	Constant	1.673	1.671	1.673	1.673	1.677	1.677
	Wald χ^2	12.68*	49.28*	32.96*	95.58*	10.58*	18.28*
9: CII	**INN**	0.001*	0.004*	0.004*	0.001*	0.001*	0.003*
	ICT	0.003*	0.006*	0.005*	0.015*	0.001*	0.007*
	Constant	1.671	1.669	1.671	1.673	1.676	1.677
	Wald χ^2	17.98*	53.68*	35.61*	86.83*	10.26*	18.18*

Note 1: PEG is per capita economic growth, PAR is patents by residents, PAN is patent by non-residents, PAT is patents filled by both residents and non-residents, RDE is research and development expenditure, RRD is researchers in research and development activities, HTX is high-technology exports, STJ is scientific and technical articles, TRM is trademark applications, CII is the composite index of innovation diffusion, TEL is telephone land lines, MOB is mobile phones, INU is internet users, INS is internet servers, FIB is fixed broadband, and CIC is the composite index of ICT penetration.

Note 2: INN represents innovation and is used as a proxy for PAR, PAN, PAT, RDE, RRD, HTX, STJ, TRM and CII; and ICT represents ICT penetration and is used as a proxy for TEL, MOB, INU, INS, FIB, and CIC.

Note 3: * and ** indicate that parameter estimates are significant at the 1% and 5% levels, respectively.

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Table 1. Empirical Results of Panel Cointegration Tests

Sample 1: PAR, ICT, PEG

	Case 1 (TEL)		Case 2 (MOB)		Case 3 (INU)		Case 4 (INS)		Case 5 (FIB)		Case 6 (CIC)	
	Tra	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**
None	249*	194.4*	396*	369.7*	454*	429.3*	225.1*	214.4*	682*	596.6*	265*	255.6*
At most 1	130*	129.1*	132*	136.2*	132*	139.6*	80.9*	82.65*	211*	217.1*	94.5	95.9
At most 2	59.5	59.5	42.7	30.98	42.7	42.7	46.2	46.2	50.6	50.6	46.3	46.3
NOC		**2**		**2**		**2**		**2**		**2**		**1**
Inferences	Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated	

Sample 2: PAN, ICT, PEG

	Case 1 (TEL)		Case 2 (MOB)		Case 3 (INU)		Case 4 (INS)		Case 5 (FIB)		Case 6 (CIC)	
	Tra	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**
None	339*	320*	303*	270.2*	298*	279.2*	441*	418.9*	633*	607.2*	278*	276.9*
At most 1	101*	108*	114*	118.6*	106*	114.4*	127*	129.3*	161*	159.8*	81.8	88.1
At most 2	33.6	33.6	52.8	52.8	38.2	38.24	51.7	51.7	60.6	60.6	39.6	39.6
NOC		**2**		**2**		**2**		**2**		**2**		**1**
Inferences	Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated	

Sample 3: PAT, ICT, PEG

	Case 1 (TEL)		Case 2 (MOB)		Case 3 (INU)		Case 4 (INS)		Case 5 (FIB)		Case 6 (CIC)	
	Tra	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**
None	240*	210.6*	344*	320.5*	459*	444.5*	369.1*	303.8*	658*	590.3*	287*	285*
At most 1	141*	109.3	117*	129.8*	120*	128.6*	148.2*	150.0*	197*	203.5*	76.3	87.3
At most 2	48.1	48.10	32.2	32.2	39.5	39.5	53.5	53.5	47.9*	47.9*	25.6	25.6
NOC		**2**		**2**		**2**		**2**		**2**		**1**
Inferences	Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated	

Sample 4: RDE, ICT, PEG

	Case 1 (TEL)		Case 2 (MOB)		Case 3 (INU)		Case 4 (INS)		Case 5 (FIB)		Case 6 (CIC)	
	Tra	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**
None	366*	317.4*	394*	341.7*	426*	401.1*	559.8*	501.5*	653*	614*	320.6*	275.3*
At most 1	138*	132.9*	149*	145.0*	125*	127.5*	167.7*	166.9*	161*	161*	129.7*	122.6*
At most 2	75.4	75.4	67.6	67.6	57.6	56.6	63.5	63.5	59.9	59.9	75.7	75.7
NOC		**2**		**2**		**2**		**2**		**2**		**2**
Inferences	Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated	

Sample 5: RRD, ICT, PEG

	Case 1 (TEL)		Case 2 (MOB)		Case 3 (INU)		Case 4 (INS)		Case 5 (FIB)		Case 6 (CIC)	
	Tra	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**
None	290*	236.3*	350*	328.8*	376.7*	310.0*	445*	386.8*	647*	584.8*	312*	284.1*
At most 1	127*	111.7	105*	104.5*	158.7*	153.6*	153*	158.8*	178*	175.8*	105*	96.1*
At most 2	81.0	81.0	48.8	48.8	61.7	61.7	45.9	45.9	60.1	60.1	63.7	63.7
NOC		**2**		**2**		**2**		**3**		**2**		**2**
Inferences	Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated	

Sample 6: HTX, ICT, PEG

	Case 1 (TEL)		Case 2 (MOB)		Case 3 (INU)		Case 4 (INS)		Case 5 (FIB)		Case 6 (CIC)	
	Tra	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**
None	322*	305.1*	395*	332.2*	513*	482*	540*	460.7*	672*	653.5*	345*	314.9*
At most 1	108*	109.7*	168*	180.2*	148*	149.5*	196*	194.5*	146*	143.9*	128*	134.7*
At most 2	62.2	62.2	40.1	40.1	60.0*	60.0*	73.6*	73.6*	70.1	70.1	50.7	50.7
NOC		**2**		**2**		**2**		**2**		**2**		**2**
Inferences	Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated	

Sample 7: STJ, ICT, PEG

	Case 1 (TEL)		Case 2 (MOB)		Case 3 (INU)		Case 4 (INS)		Case 5 (FIB)		Case 6 (CIC)	
	Tra	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**
None	427*	392.9*	499*	451.3*	618*	520.6*	540*	460.7*	672*	653.5*	345*	314.9*
At most 1	243*	209.5*	168*	179.2*	217*	227.2*	196*	194.5*	146*	143.4*	128*	134.7*
At most 2	145*	145.0*	51.95	51.95	60.8	60.8	73.6	73.6	70.1	70.1	50.7	50.7
NOC		**2**		**2**		**2**		**2**		**2**		**2**
Inferences	Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated	

Sample 8: TRM, ICT, PEG

	Case 1 (TEL)		Case 2 (MOB)		Case 3 (INU)		Case 4 (INS)		Case 5 (FIB)		Case 6 (CIC)	
	Tra	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**
None	245*	236.6*	363*	346.0*	414.4*	379.2*	701*	596.4*	720*	668.0*	265.3*	271.3*
At most 1	90.7	95.6	114*	126.0*	140.9*	150.7*	218*	207.6*	191*	198.2*	84.77	93.6
At most 2	52.8	52.8	40.97	40.97	51.78	51.78	93.5	93.5	58.2	58.2	37.85	37.9
NOC		**1**		**2**		**2**		**3**		**2**		**2**
Inferences	Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated	

Sample 9: CII, ICT, PEG

	Case 1 (TEL)		Case 2 (MOB)		Case 3 (INU)		Case 4 (INS)		Case 5 (FIB)		Case 6 (CIC)	
	Tra	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**
None	317*	298.2*	337.6*	354.5*	377*	399*	538*	465*	735*	713.3*	231*	222.5*
At most 1	119*	127.5*	91.1	100.8	90.6	93.6	188*	172*	158*	153.3*	91.5	95.6
At most 2	53.2	53.2	39.9	39.9	57.9	57.9	99.6	99.6	78.4	78.4	50.4	50.4
NOC		**1**		**1**		**1**		**2**		**2**		**1**
Inferences	Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated	

Note 1: PEG is per capita economic growth, PAR is patents by residents, PAN is patent by non-residents, PAT is patents filled by both residents and non-residents, RDE is research and development expenditure, RRD is researchers in research and development activities, HTX is high-technology exports, STJ is scientific and technical articles, TRM is trademark applications, CII is the composite index of innovation diffusion, TEL is telephone land lines, MOB is mobile phones, INU is internet users, INS is internet servers, FIB is fixed broadband, and CIC is the composite index of ICT penetration.

Note 2: ICT stands for ICT penetration and indicates TEL, MOB, INU, INS, FIB, or CIC.

Note 3: Tra is trace statistics; Max is maximum Eigenvalue statistics; and NOC is number of cointegrating vector.

Note 4: * indicates that the test statistics are significant at the 1% level.

Table 2. Empirical Results of Panel Granger Causality Test

Dependent Variable | **Independent variables and ECT_{-1}**

Setup 1: Between PAR, ICT penetration, and economic growth

	Case 1 (TEL)				**Case 2 (MOB)**				**Case 3 (INU)**			
	ΔPAR	**ΔTEL**	**ΔPEG**	**ECT_{-1}**	**ΔPAR**	**ΔMOB**	**ΔPEG**	**ECT_{-1}**	**ΔPAR**	**ΔINU**	**ΔPEG**	**ECT_{-1}**
ΔPAR	-----	9.30*	0.98	-0.007	-----	6.65**	4.67	-0.0003	-----	4.54	8.32*	-0.0003
ΔICT	6.44**	-----	8.28*	-0.006	4.02	-----	8.09*	-0.003*	6.35**	-----	30.11*	-0.02
ΔPEG	12.96*	3.85	-----	-0.004*	9.53*	11.9*	-----	-0.001*	10.4	6.81**	-----	-0.0001*

	Case 4 (INS)				**Case 5 (FIB)**				**Case 6 (CIC)**			
	ΔPAR	**ΔINS**	**ΔPEG**	**ECT_{-1}**	**ΔPAR**	**ΔFIB**	**ΔPEG**	**ECT_{-1}**	**ΔPAR**	**ΔCIC**	**ΔPEG**	**ECT_{-1}**
ΔPAR	-----	8.26*	12.0*	-0.009	-----	1.62	10.23*	-0.004	-----	7.68**	1.41	-0.0004*
ΔICT	5.62***	-----	13.2*	-0.025	5.40***	-----	9.33*	-0.055	6.23**	-----	24.2*	-0.0001
ΔPEG	9.29*	18.2*	-----	-0.014*	10.9*	11.9*	-----	-0.002*	15.4*	31.5*	-----	-0.003*

Setup 2: Between PAN, ICT penetration, and economic growth

	Case 1 (TEL)				**Case 2 (MOB)**				**Case 3 (INU)**			
	ΔPAN	**ΔTEL**	**ΔPEG**	**ECT_{-1}**	**ΔPAN**	**ΔMOB**	**ΔPEG**	**ECT_{-1}**	**ΔPAN**	**ΔINU**	**ΔPEG**	**ECT_{-1}**
ΔPAN	-----	11.8*	5.30**	-0.002	-----	14.7*	3.11	-0.0003	-----	10.9*	7.56**	-0.01
ΔICT	4.74***	-----	7.85*	-0.0001	11.14*	-----	15.5*	-0.003*	14.6*	-----	9.07*	-0.02
ΔPEG	4.90***	7.94*	-----	-0.003*	3.89	24.2*	-----	-0.001*	4.39	3.92	-----	-0.0004*

	Case 4 (INS)				**Case 5 (FIB)**				**Case 6 (CIC)**			
	ΔPAN	**ΔINS**	**ΔPEG**	**ECT_{-1}**	**ΔPAN**	**ΔFIB**	**ΔPEG**	**ECT_{-1}**	**ΔPAN**	**ΔCIC**	**ΔPEG**	**ECT_{-1}**
ΔPAN	-----	4.41*	4.64***	-0.001	-----	2.11	6.39*	-0.001	-----	12.59*	1.89	-0.002
ΔICT	3.26	-----	13.0*	-0.011	1.70	-----	1.36	-0.030	14.9*	-----	25.0*	-0.0003
ΔPEG	11.55*	10.6*	-----	-0.007*	5.95**	12.8*	-----	-0.001*	5.99*	43.8*	-----	-0.001*

Setup 3: Between PAT, ICT penetration, and economic growth

	Case 1 (TEL)				**Case 2 (MOB)**				**Case 3 (INU)**			
	ΔPAT	**ΔTEL**	**ΔPEG**	**ECT_{-1}**	**ΔPAT**	**ΔMOB**	**ΔPEG**	**ECT_{-1}**	**ΔPAT**	**ΔINU**	**ΔPEG**	**ECT_{-1}**
ΔPAT	-----	9.67*	4.78***	-0.001*	-----	6.71**	5.11***	-0.0001	-----	10.9*	3.72	-0.006
ΔICT	1.02	-----	8.08*	-0.0001	6.74**	-----	19.1*	-0.003*	4.41***	-----	21.5*	-0.024
ΔPEG	3.64	6.46*	-----	-0.005*	7.46*	25.9*	-----	-0.001*	6.40*	5.20**	-----	-0.002*

	Case 4 (INS)				**Case 5 (FIB)**				**Case 6 (CIC)**			
	ΔPAT	**ΔINS**	**ΔPEG**	**ECT_{-1}**	**ΔPAT**	**ΔFIB**	**ΔPEG**	**ECT_{-1}**	**ΔPAT**	**ΔCIC**	**ΔPEG**	**ECT_{-1}**
ΔPAT	-----	8.67*	8.48*	-0.008	-----	4.02	1.74	-0.002	-----	8.73*	4.19	-0.0002*
ΔICT	2.85	-----	12.9*	-0.027	7.01*	-----	5.31*	-0.051	7.88*	-----	21.8*	-0.001
ΔPEG	3.89	17.8*	-----	-0.015*	3.37	11.9*	-----	-0.003*	7.22*	33.2*	-----	-0.002*

Setup 4: Between RDE, ICT penetration, and economic growth

	Case 1 (TEL)				Case 2 (MOB)				Case 3 (INU)			
	ΔRDE	**ΔTEL**	**ΔPEG**	**ECT_{-1}**	**ΔRDE**	**ΔMOB**	**ΔPEG**	**ECT_{-1}**	**ΔRDE**	**ΔINU**	**ΔPEG**	**ECT_{-1}**
ΔRDE	-----	15.2*	7.23**	-0.004	-----	2.07	4.32	-0.001	-----	6.97**	4.72	-0.003
ΔICT	4.12	-----	8.40*	-0.003	14.0*	-----	18.1*	-0.009	8.04*	-----	7.06*	-0.009
ΔPEG	7.98*	12.5*	-----	-0.002*	4.09	8.73*	-----	-0.001*	5.40**	4.46***	-----	-0001*

	Case 4 (INS)				Case 5 (FIB)				Case 6 (CIC)			
	ΔRDE	**ΔINS**	**ΔPEG**	**ECT_{-1}**	**ΔRDE**	**ΔFIB**	**ΔPEG**	**ECT_{-1}**	**ΔRDE**	**ΔCIC**	**ΔPEG**	**ECT_{-1}**
ΔRDE	-----	2.40	5.99**	-0.002	-----	5.32***	3.96	-0.004	-----	8.65*	0.84	-0.0003
ΔICT	2.06	-----	10.65*	-0.028	3.91	-----	2.33	-0.065	1.50	-----	6.068*	-0.0002
ΔPEG	8.97**	10.4*	-----	-0.021*	6.09***	19.9*	-----	-0.007*	4.88***	15.3*	-----	-0.003*

Setup 5: Between RRD, ICT penetration, and economic growth

	Case 1 (TEL)				Case 2 (MOB)				Case 3 (INU)			
	ΔRRD	**ΔTEL**	**ΔPEG**	**ECT_{-1}**	**ΔRRD**	**ΔMOB**	**ΔPEG**	**ECT_{-1}**	**ΔRRD**	**ΔINU**	**ΔPEG**	**ECT_{-1}**
ΔRRD	-----	5.95**	1.17	-0.001	-----	1.61	2.32	-0.006	-----	10.9*	1.196	-0.001
ΔICT	9.32*	-----	4.24	-0.0004	16.5*	-----	40.3*	-0.002*	4.35	-----	5.12***	-0.012
ΔPEG	5.02***	5.68***	-----	-0.003*	9.57*	2.24	-----	-0.15*	8.19*	2.16	-----	-0.001*

	Case 4 (INS)				Case 5 (FIB)				Case 6 (CIC)			
	ΔRRD	**ΔINS**	**ΔPEG**	**ECT_{-1}**	**ΔRRD**	**ΔFIB**	**ΔPEG**	**ECT_{-1}**	**ΔRRD**	**ΔCIC**	**ΔPEG**	**ECT_{-1}**
ΔRRD	-----	6.61*	4.62	-0.0004	-----	7.74*	0.73	-0.0005	-----	8.10*	3.04	-0.009
ΔICT	11.0*	-----	8.76*	-0.0001	2.91	-----	37.7*	-0.007	5.17**	-----	14.5*	-0.004
ΔPEG	1.97	24.4*	-----	-0.001*	4.10***	33.7*	-----	-0.008**	9.98*	21.5*	-----	-0.002*

Setup 6: Between HTX, ICT penetration, and economic growth

	Case 1 (TEL)				Case 2 (MOB)				Case 3 (INU)			
	ΔHTX	**ΔTEL**	**ΔPEG**	**ECT_{-1}**	**ΔHTX**	**ΔMOB**	**ΔPEG**	**ECT_{-1}**	**ΔHTX**	**ΔINU**	**ΔPEG**	**ECT_{-1}**
ΔHTX	-----	11.97	17.41**	-0.002*	-----	11.98	15.0*	-0.0002	-----	4.208	6.896**	-0.001
ΔICT	5.597**	-----	8.017*	-0.001	19.7*	-----	6.99*	-0.001	4.313*	-----	8.38*	-0.007
ΔPEG	7.075**	15.24*	-----	-0.002*	10.4	6.295*	-----	-0.001*	12.48*	4.99**	-----	-0.003*

	Case 4 (INS)				Case 5 (FIB)				Case 6 (CIC)			
	ΔHTX	**ΔINS**	**ΔPEG**	**ECT_{-1}**	**ΔHTX**	**ΔFIB**	**ΔPEG**	**ECT_{-1}**	**ΔHTX**	**ΔCIC**	**ΔPEG**	**ECT_{-1}**
ΔHTX	-----	3.231	8.902*	-0.002	-----	3.59	7.17*	-0.006	-----	9.24*	18.4*	-0.001
ΔICT	8.464*	-----	12.85*	-0.006	7.40*	-----	2.74	-0.033	9.90*	-----	24.4*	-0.003
ΔPEG	9.06*	6.14**	-----	-0.004*	13.59*	23.1*	-----	-0.19*	11.8*	53.1*	-----	-0.001*

Setup 7: Between STJ, ICT penetration, and economic growth

	Case 1 (TEL)				Case 2 (MOB)				Case 3 (INU)			
	ΔSTJ	**ΔTEL**	**ΔPEG**	**ECT_{-1}**	**ΔSTJ**	**ΔMOB**	**ΔPEG**	**ECT_{-1}**	**ΔSTJ**	**ΔINU**	**ΔPEG**	**ECT_{-1}**
ΔSTJ	-----	12.23*	14.83*	-0.003	-----	21.82*	5.11*	-0.001	-----	14.85*	3.344	-0.001
ΔICT	7.078**	-----	34.98*	-0.0002	13.2*	-----	23.8*	-0.004	14.56*	-----	12.55*	-0.023
ΔPEG	10.14*	4.82***	-----	-0.005*	11.98*	22.6*	-----	-0.002*	11.64*	15.21*	-----	-0.001*

	Case 4 (INS)				Case 5 (FIB)				Case 6 (CIC)			
	ΔSTJ	**ΔINS**	**ΔPEG**	**ECT$_{-1}$**	**ΔSTJ**	**ΔFIB**	**ΔPEG**	**ECT$_{-1}$**	**ΔSTJ**	**ΔCIC**	**ΔPEG**	**ECT$_{-1}$**
ΔSTJ	-----	4.65*	5.94**	-0.004	-----	4.36***	1.83	-0.007	-----	15.7*	9.70	-0.012
ΔICT	4.46***	-----	11.2*	-0.015	5.46*	-----	9.40*	-0.0.39	0.672	-----	34.2*	-0.001
ΔPEG	0.81	6.47**	-----	-0.012*	3.87	9.44*	-----	-0.001*	8.71	23.7*	-----	-0.004*

Setup 8: Between TRM, ICT penetration, and economic growth

	Case 1 (TEL)				Case 2 (MOB)				Case 3 (INU)			
	ΔTRM	**ΔTEL**	**ΔPEG**	**ECT$_{-1}$**	**ΔTRM**	**ΔMOB**	**ΔPEG**	**ECT$_{-1}$**	**ΔTRM**	**ΔINU**	**ΔPEG**	**ECT$_{-1}$**
ΔTRM	-----	30.34	17.18*	-0.001	-----	12.3*	12.2	-0.004	-----	3.639	21.3*	-0.001
ΔICT	18.4	-----	14.9*	-0.001	0.948	-----	40.3*	-0.003	10.4*	-----	10.5*	-0.009
ΔPEG	3.36	7.75*	-----	-0.003*	2.52	31.4*	-----	-0.004*	5.39*	6.27*	-----	-0.002*

	Case 4 (INS)				Case 5 (FIB)				Case 6 (CIC)			
	ΔTRM	**ΔINS**	**ΔPEG**	**ECT$_{-1}$**	**ΔTRM**	**ΔFIB**	**ΔPEG**	**ECT$_{-1}$**	**ΔTRM**	**ΔCIC**	**ΔPEG**	**ECT$_{-1}$**
ΔTRM	-----	8.948*	14.31*	-0.004	-----	4.08***	13.67*	-0.002	-----	7.515*	6.257**	-0.0003
ΔICT	8.315*	-----	8.342*	-0.003	1.092	-----	0.65	-0.029	28.66**	-----	21.76*	-0.001
ΔPEG	3.837	12.42*	-----	-0.002*	6.997*	14.31**	-----	-0.002*	3.803	26.02*	-----	-0.002*

Setup 9: Between CII, ICT penetration, and economic growth

	Case 1 (TEL)				Case 2 (MOB)				Case 3 (INU)			
	ΔCII	**ΔTEL**	**ΔPEG**	**ECT$_{-1}$**	**ΔCII**	**ΔMOB**	**ΔPEG**	**ECT$_{-1}$**	**ΔCII**	**ΔINU**	**ΔPEG**	**ECT$_{-1}$**
ΔCII	-----	62.3*	10.39*	-0.001	-----	3.84	24.3*	-0.003	-----	12.97*	15.87*	-0.003
ΔICT	7.74*	-----	26.65*	-0.001	26.15*	-----	31.68*	-0.001	3.767	-----	14.05*	-0.017
ΔPEG	8.50*	3.92	-----	-0.005*	3.06	30.4*	-----	-0.001*	6.007**	6.339**	-----	-0.003*

	Case 4 (INS)				Case 5 (FIB)				Case 6 (CIC)			
	ΔCII	**ΔINS**	**ΔPEG**	**ECT$_{-1}$**	**ΔCII**	**ΔFIB**	**ΔPEG**	**ECT$_{-1}$**	**ΔCII**	**ΔCIC**	**ΔPEG**	**ECT$_{-1}$**
ΔCII	-----	41.8*	11.89*	-0.002	-----	15.46*	22.02*	-0.01	-----	19.16*	11.12*	-0.001
ΔICT	3.559	-----	13.41*	-0.018	20.0*	-----	7.28*	-0.08	26.52*	-----	33.14*	-0.716
ΔPEG	6.195**	7.963*	-----	-0.014*	4.538*	14.73*	-----	-0.002*	7.534*	27.79*	-----	-0.006*

Note 1: PEG is per capita economic growth, PAR is patents by residents, PAN is patent by non-residents, PAT is patents filled by both residents and non-residents, RDE is research and development expenditure, RRD is researchers in research and development activities, HTX is high-technology exports, STJ is scientific and technical articles, TRM is trademark applications, CII the is composite index of innovation diffusion, TEL is telephone land lines, MOB is mobile phones, INU is internet users, INS is internet servers, FIB is fixed broadband, CIC is the composite index of ICT penetration.

Note 2: ICT stands for ICT penetration and indicates TEL, MOB, INU, INS, FIB, or CIC.

Note 3: ECT$_{-1}$ is the lagged error-correction term.

***Note 4*:** *, **, and *** indicate that parameter estimates are significant at the 1%, 5%, and 10% levels, respectively.

Table 3. Summary of Short-run Granger Causality Results

Setups	Cases	Possible Causalities		
		INN and ICT	INN and PEG	ICT and PEG
	1	PAR ⇔ TEL	PAR ⇒ PEG	TEL ⇐ PEG
1	2	PAR ⇐ MOB	PAR ⇒ PEG	MOB ⇔ PEG
	3	PAR ⇒ INU	PAR ⇐ PEG	INU ⇔ PEG
	4	PAR ⇔ INS	PAR ⇔ PEG	INS ⇔ PEG
	5	PAR ⇒ FIB	PAR ⇔ PEG	FIB ⇔ PEG
	6	PAR ⇔ CIC	PAR ⇒ PEG	CIC ⇔ PEG
	1	PAN ⇔ TEL	PAN ⇔ PEG	TEL ⇔ PEG
2	2	PAN ⇔ MOB	PAN ∤ PEG	MOB ⇔ PEG
	3	PAN ⇔ INU	PAN ⇐ PEG	INU ⇐ PEG
	4	PAN ⇐ INS	PAN ⇔ PEG	INS ⇔ PEG
	5	PAN ∤ FIB	PAN ⇔ PEG	FIB ⇒ PEG
	6	PAN ⇔ CIC	PAN ⇒ PEG	CIC ⇔ PEG
	1	PAT ⇐ TEL	PAT ⇐ PEG	TEL ⇔ PEG
3	2	PAT ⇔ MOB	PAT ⇔ PEG	MOB ⇔ PEG
	3	PAT ⇔ INU	PAT ⇒ PEG	INU ⇔ PEG
	4	PAT ⇐ INS	PAT ⇐ PEG	INS ⇔ PEG
	5	PAT ⇒ FIB	PAT ∤ PEG	FIB ⇔ PEG
	6	PAT ⇔ CIC	PAT ⇒ PEG	CIC ⇔ PEG
	2	RDE ⇐ TEL	RDE ⇔ PEG	TEL ⇔ PEG
4	2	RDE ⇒ MOB	RDE ∤ PEG	MOB ⇔ PEG
	3	RDE ⇔ INU	RDE ⇒ PEG	INU ⇔ PEG
	4	RDE ∤ INS	RDE ⇔ PEG	INS ⇔ PEG
	5	RDE ⇐ FIB	RDE ⇒ PEG	FIB ⇒ PEG
	6	RDE ⇐ CIC	RDE ⇒ PEG	CIC ⇔ PEG
	1	RRD ⇔ TEL	RRD ⇒ PEG	TEL ⇒ PEG
5	2	RRD ⇒ MOB	RRD ⇒ PEG	MOB ⇐ PEG
	3	RRD ⇐ INU	RRD ⇒ PEG	INU ⇐ PEG
	4	RRD ⇔ INS	RRD ∤ PEG	INS ⇔ PEG
	5	RRD ⇐ FIB	RRD ⇒ PEG	FIB ⇔ PEG
	6	RRD ⇔ CIC	RRD ⇒ PEG	CIC ⇔ PEG

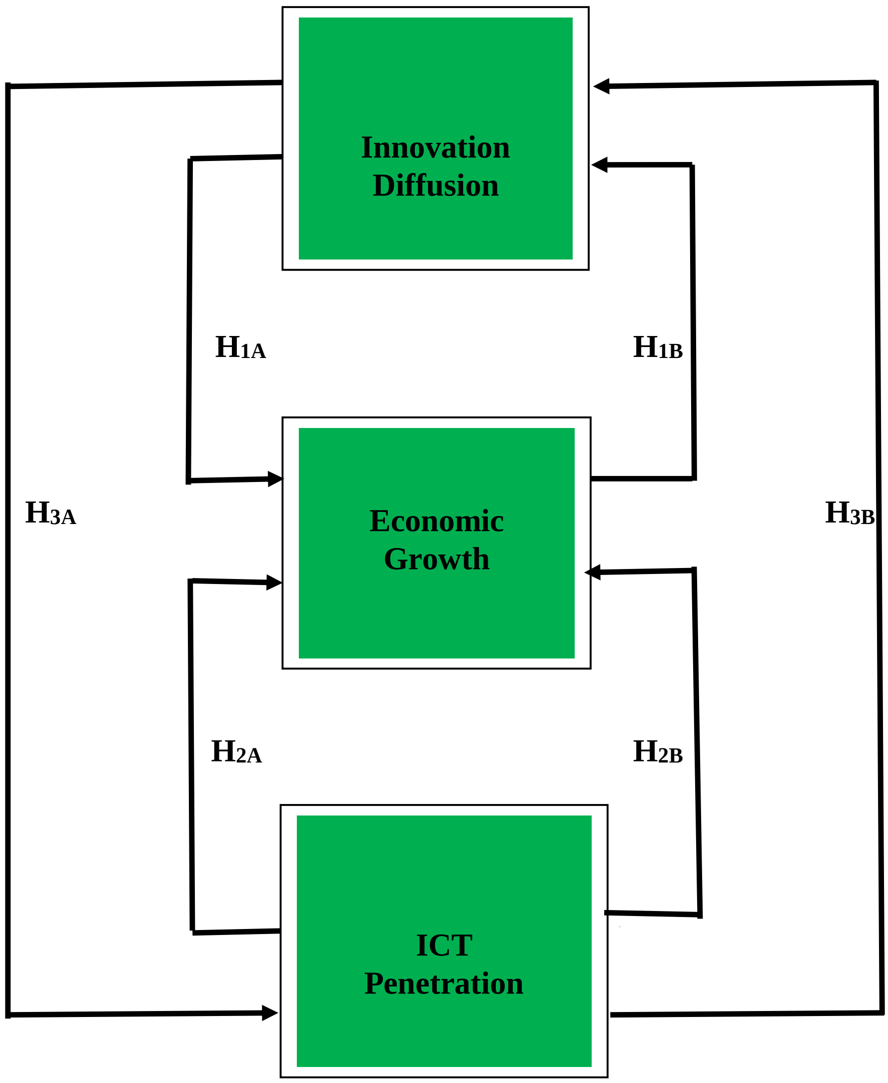
	1	**HTX ⇒ TEL**	**HTX ⇔ PEG**	**TEL ⇔ PEG**
6	**2**	**HTX ⇒ MOB**	**HTX ⇐ PEG**	**MOB ⇔ PEG**
	3	**HTX ⇒ INU**	**HTX ⇔ PEG**	**INU ⇔ PEG**
	4	**HTX ⇒ INS**	**HTX ⇔ PEG**	**INS ⇔ PEG**
	5	**HTX ⇒ FIB**	**HTX ⇔ PEG**	**FIB ⇒ PEG**
	6	**HTX ⇔ CIC**	**HTX ⇔ PEG**	**CIC ⇔ PEG**
	7	**STJ ⇔ TEL**	**STJ ⇔ PEG**	**TEL ⇔ PEG**
7	**2**	**STJ ⇔ MOB**	**STJ ⇔ PEG**	**MOB ⇔ PEG**
	3	**STJ ⇔ INU**	**STJ ⇒ PEG**	**INU ⇔ PEG**
	4	**STJ ⇔ INS**	**STJ ⇐ PEG**	**INS ⇔ PEG**
	5	**STJ ⇔ FIB**	**STJ ∤ PEG**	**FIB ⇔ PEG**
	6	**STJ ⇐ CIC**	**STJ ∤ PEG**	**CIC ⇔ PEG**
	1	**TRM ∤ TEL**	**TRM ⇐ PEG**	**TEL ⇔ PEG**
8	**2**	**TRM ⇐ MOB**	**TRM ∤ PEG**	**MOB ⇔ PEG**
	3	**TRM ⇒ INU**	**TRM ⇔ PEG**	**INU ⇔ PEG**
	4	**TRM ⇔ INS**	**TRM ⇐ PEG**	**INS ⇔ PEG**
	5	**TRM ⇐ FIB**	**TRM ⇔ PEG**	**FIB ⇒ PEG**
	6	**TRM ⇔ CIC**	**TRM ⇐ PEG**	**CIC ⇔ PEG**
	1	**CII ⇔ TEL**	**CII ⇔ PEG**	**TEL ⇐ PEG**
9	**2**	**CII ⇒ MOB**	**CII ⇐ PEG**	**MOB ⇔ PEG**
	3	**CII ⇐ INU**	**CII ⇔ PEG**	**INU ⇔ PEG**
	4	**CII ⇐ INS**	**CII ⇔ PEG**	**INS ⇔ PEG**
	5	**CII ⇔ FIB**	**CII ⇔ PEG**	**FIB ⇔ PEG**
	6	**CII ⇔ CIC**	**CII ⇔ PEG**	**CIC ⇔ PEG**

Note 1: PEG is per capita economic growth, PAR is patents by residents, PAN is patent by non-residents, PAT is patents filled by both residents and non-residents, RDE is research and development expenditure, RRD is researchers in research and development activities, HTX is high-technology exports, STJ is scientific and technology articles, TRM is trademark applications, CII is the composite index of innovation diffusion, TEL is telephone land lines, MOB is mobile phones, INU is internet users, INS is internet servers, FIB is fixed broadband, and CIC is the composite index of ICT penetration.

Note 2: ICT stands for ICT penetration and indicates TEL, MOB, INU, INS, FIB, or CIC.

Note 3: INN stands for innovation diffusion and indicates PAR, PAN, PAT, RDE, RRD, THE, STJ, TRM, or CII.

Note 4: **⇐/ ⇒/ ⇔** indicate the direction of Granger causality; **∤** signifies non-Granger causality.



Notes:
H_{1A}: Innovation diffusion Granger-causes economic growth.
H_{2A}: ICT penetration Granger-causes economic growth.
H_{3A}: ICT penetration Granger-causes innovation diffusion.
Subscript B (in place of A) signifies Granger causality in reverse order.

Figure 1: Summary of the Possible Causal Links Among the Three Sets of Variables