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Short-term and long-term dynamics of venture capital and economic growth in a digital economy: A study of European countries

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ABSTRACT

There has been a significant transformation in the diffusion of information and communication technology (ICT), development of the venture capital industry, and economic growth in European countries over the past three decades. Using vector error-correction modelling, we examine the possible interrelations between venture capital investment, ICT infrastructure, and economic growth, based on annual data from 25 European countries between 1989 and 2016. Specifically, we examine the direction of Granger causality between these variables. We find that the variables are cointegrated. Our empirical results also illustrate that both economic growth and the development of ICT infrastructure impact all stages of venture capital investment (early, late, and overall VC investment) in the long run. The study also shows that economic growth and late-stage venture capital investment impact internet usage; and internet usage and late-stage venture capital impact economic growth in the long run. The results also reveal strong inter-linkages between the variables in the short run. Overall, empirical results suggest that policy-makers should give special attention to an integrated policy approach for the co-development of the ICT infrastructure, venture capital, and economic growth in Europe.

1. Introduction

The European economies have undergone a major transformation over the last three decades. While some economies have achieved sustained economic growth, many have experienced lacklustre growth due to declining total factor productivity and intense competition from other countries [1]. To ensure countries achieve sustained economic growth and enhanced global competitiveness, governments in Europe have invested significant resources to develop and upgrade the information and communication technology infrastructure [62]. To encourage greater innovation and entrepreneurship, these economies have also embarked on ambitious plans to nurture a vibrant venture capital (VC) ecosystem [2].

Venture capital (VC) plays a critical role in the creation of wealth and prosperity in an economy [3–5]. Venture capital is a specialized form of financial intermediation or investment, which provides funding to innovative new ventures with high-growth prospects in exchange for equity stakes in the companies [6,7,10]. VC likely produces several positive externalities, namely, innovation, job creation, increased standard of living, investment in infrastructure, service sector growth, increased productivity, and increased value of VC-financed firms due to the provisions of both managerial skills and competencies (see Refs. [11,12]).

We should highlight several issues related to studies of venture capital. First, while the theoretical foundation has been established with regards to VC serving as a stimulator for economic growth, there is still much work to be done to empirically confirm the theory [13]. Second, the results of studies on venture capital activities have produced a wide range of conclusions that vary considerably (see, for example, [14]. Third, a better understanding of the factors that play a vital role in motivating venture capital investment on a macro level can lend additional insight to policymakers as they design economic, technology and financial policies that can promote the growth of venture capital and, possibly, in turn, economic growth (see, for instance, [15]). This study focuses on the third issue as we attempt to provide greater insight into the macro-level factors that are critical to

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stimulating venture capital investment.

The literature confirms that there are several factors that contribute to venture capital investment (see Ref. [16]). Fundamentally, these factors correspond to foundations that provide the basic structure of an economy[1]: macroeconomic stability and the development/standard of institutional systems (e.g., the legal system, rule of law, quality of accounting standards, quality of regulation and regulatory compliance, quality of the workforce, cultural orientation, and the availability of other basic infrastructure such as, information and communication technology (ICT) infrastructure).

Since the emergence of endogenous growth theory, several empirical studies have considered how economic growth might contribute to venture capital investment (for example [17–20]), how economic growth might impact ICT infrastructure [21–25], and how ICT infrastructure might impact venture capital investment [26]. However, there is still a dearth of research and insight on the role of ICT infrastructure in stimulating venture capital investment, especially at different stages.

The contributions of this study are three-fold. First, the results of this study shed additional light on the Granger-causal relationships between economic growth and venture capital investment, and between economic growth and ICT infrastructure in European countries. This contribution is important as earlier empirical results on the nature of the relationships between these variables are mixed. In some cases (e.g. Ref. [26]), the results suggest that economic growth may actually hinder venture capital investment. Second, this study examines the trivariate Granger-causal relationship between economic growth, venture capital investment, and ICT infrastructure. To the best of our knowledge, this is the first empirical study that simultaneously considers the possible Granger-causal relationships between all three variables. Third, based on the empirical analysis, this study will 'tease-out' key policies pertaining to ICT usage, VC industry, and economic growth stimulating policies that would enable the European countries to achieve long-term sustainable economic development.

The paper is structured as follows. Section 2 offers a review of the literature, discussing what previous papers have established in this field and highlighting the unique contributions of this study. Section 3 describes the methodology that is used. Section 4 discusses the empirical results. Section 5 is devoted to hypotheses validation and discusses the estimation limitations. Section 6 offers pertinent policy implications.

2. Literature review

2.1. Economic growth and ICT infrastructure

The relationship between economic growth and investment in ICT infrastructure is well established in the literature. Early studies note the clear correlation between high economic development and highly developed telecommunications infrastructure (for example, [27]; and [28]). ICT might contribute to economic growth through several channels[2]: 1) by serving as an important revenue-earning sector in an economy; 2) by improving market reach for both resources and markets which in turn enables economies of scale; and 3) by improving products and services which enables the firm to pursue economies of scale. Alternatively, other studies have shown that economic growth will increase demand for ICT services which leads to increased ICT infrastructure [15,29]; and [30]. In general, recent studies are interested in the direction of causality of this relationship between ICT and economic growth. Four schools of thought are discussed below.

The first school of thought puts forward the 'Supply-Leading Hypothesis' (SLH), which suggests that ICT development leads to economic growth. The rationale for this relationship stems from the fact that ICT investment enhances growth in the ICT industry, thus creating employment and stimulating economic growth. ICT investment is also seen as an important enabler for raising the productivity and efficiency within the economy. It enables economic agents to enhance their reach for information, knowledge, resources, and markets more easily. High-quality infrastructure also enables firms to enhance the richness of their products and services by catering to specific needs of a wider spectrum of their clientele, all of which contribute to economic growth. Among the proponents of this school of thought are [22,31–36]; and [37].

The second school of thought comprises the proponents of the 'Demand-Following Hypothesis' (DFH), who postulate that economic growth causes ICT development. The rationale for this argument is related to the fact that when income levels increase, the various key stakeholders in the economy will demand more sophisticated technology that enables them to access information and knowledge to enhance their competitiveness and quality of life. Among the studies that support this hypothesis are [29,32,33,38]; and [39].

The third school of thought advances the 'Feedback Loop Hypothesis' (FLH), which argues that there is a complex relationship between ICT infrastructure investment and economic growth. That is, ICT investments contribute to economic growth as suggested by proponents of SLH. However, economic growth increases the demand for high-quality ICT infrastructure, thus supporting the DFH school of thought. Studies that have supported the FLH include [33,38,40] [8,9,41]; Shiu and Lam, (2008b), and [42].

The fourth school of thought puts forth the 'Neutrality Hypothesis' (NH), which argues that there is no causal link between ICT infrastructure investment and economic growth. Their line of argument stems from the fact that ICT infrastructure is significantly smaller than other investments such as the development of physical assets (land, roads, ports and other infrastructure development), human capital, and other non-ICT related technology that drive the core sectors of the economy. Thus, ICT investment has a negligible impact on economic growth and vice-versa. Studies here include [29,32,33,36]; and [43].[3]

2.2. Economic growth and venture capital investment

The relationship between the development of the VC industry and economic development has received considerable attention from industry analysts, policy-makers, and researchers due to the role of VCs in providing alternate funding for innovative, high-technology and high-risk firms. Several studies show that VC development contributes to economic development by nurturing the development of highly innovative firms [5,44]. In some instances, innovative firms can be important disrupters that give them a competitive edge over incumbent firms in the global market. Alternatively, perhaps more advanced countries must establish new sources of funding (e.g. venture capital) to support the development of risky and innovative firms. As an economy moves up the innovation value chain, the pool of VC funding increases. The literature consists of four schools of thoughts regarding the direction of causality for economic growth and venture capital investment.

In the context of SLH, studies have argued that the development of the VC industry contributes to economic growth. The economic rationale stems from the fact that innovation is critical for spurring new sources of growth; hence, the VC industry plays a crucial role in supporting high-risk innovative firms and ventures, which traditional financial markets could not provide capital for. For example, the economic growth of the US in the 1990s was primarily driven by VC-funded technology firms that made both incremental and radical innovations in ICT, science, technology, engineering, mathematics (STEM), life sciences, pharmaceutical and medical areas that, in turn, transformed the global economic landscape (see, for instance, [45]; and [46]).

[1] [6,50]; and [19].

[2] See, for example, [68,69]; and [70].

[3] As is evident by this review, some studies support more than one hypothesis, depending on the sample and the period that is covered.

[47] demonstrate that the effect of venture capital investment on economic and innovation development parameters is significant. By showing significant VCI influence on GDP, it is clear how important it is to develop an innovation economy by fostering venture capital inflows. It is important to treat venture capital investments as the 'cause' rather than the 'effect' of the development process. Due to its delayed effect, venture investment introduces progressive growth in the short- and long-term by creating competitiveness and shaping the innovation-based economy. Venture capital investment promotes entrepreneurs, exports, employment opportunities, technological growth, economic growth and products, which in turn improves the standard of living of the people [48]. suggests that the replacement of centrally planned economies with free-market economies stimulates the demand for venture capital. A government-created "enabling framework" is first needed in developing countries to create an attractive playing field and entrepreneurial infrastructure for venture capitalists. Other empirical studies that have supported the SLH include [12]; Keuschnigg, (2004) and Samila and Sorenson, (2011).

On the other hand, the proponents of DFH have argued that, as economic growth intensifies, the wealth that is generated is invested to enhance the national innovation ecosystem by increasing investments in regional corridors, with highly concentrated technology-driven firms that power new technological developments and discoveries. These new discoveries have the potential to spawn new sources of economic growth. To support highly innovative firms, many OECD and developing countries have opened a wide range of resources to develop the VC industry. These financial resources include permitting institutional investors such as pension funds, business angels, and government funds to grow the pool of VC funding [45]. There are several empirical studies that support the DFH and among them are [12,14,15,49]; and [30].

There are a few empirical studies that support the FLH, which suggest that there is a strong feedback loop between the two variables for several countries, see, for example, [14]; and [12]. These studies argue that a growing VC industry will raise the number of firms undertaking innovations, which will spur new sectors and sources of economic growth.

Finally, some studies suggest that the NH holds and that there is no causal relationship between VC investment and economic growth for some countries [12,50].

2.3. Venture capital investment and ICT infrastructure

Interestingly, there is little research empirically examining the relationship between VC investment and ICT infrastructure, although casual evidence suggests that ICT companies are major recipients of VC funding in many OECD countries. For example, in Europe, which is the focus of our analysis, more than one-third of VC investments were for ICT companies [51]. A majority of the studies in the literature have shown a *correlation* between VC investment and ICT infrastructure development [51,52]. However, to the best of our knowledge, there are no studies that have focused on the direction of *causality* between the two variables using rigorous econometric analysis. As such, this study attempts to address this shortcoming in the literature. While this topic is not well-trodden ground, there is a reason to suspect that there is indeed a causal relationship between VC investment and ICT infrastructure, given that both the VC and ICT industries have undergone major transformations over the last two decades. There is likely a relationship between the two variables due to the fact that ICT-oriented businesses, those that create ICT infrastructure or provide ICT services, are often financed through VC (see, for example, [53–56]).

Some theories and studies would suggest that ICT causes VC. For example, the rapid ICT diffusion and demand for ICT services across the globe over the last three decades have intensified R&D activities and have led to the emergence of new ICT start-ups. These start-ups contribute to the development of new and innovative ICT infrastructure, including software and applications. One of the challenges encountered by many of these start-ups includes access to the much-needed capital for R&D and commercialisation activities. To address the shortage of high-risk capital for these risky and innovative firms, the VC industry in many countries within the EU and other countries was established. Governments in these countries realized that traditional financial systems would not provide sufficient funding for these high-risk firms. Hence, many governments created incentives to nurture 'home-grown' ICT industries to power the next generation's technology and applications. These new innovations were envisaged to not only raise the competitiveness of the broader economy but also to create an ICT industry that is a revenue generator for the nation (see, for example, [45,51,52]; and [57]).

Other theories and studies suggest that the development of ICT infrastructure contributes to the development of the VC industry. Key support for this relationship is based on the argument that, VC by its nature, funds only firms that are innovative and have a potential to generate returns within 10 years. Innovative firms here are defined as being able to generate patents or IPs that can be commercialised. A study by Ref. [58] shows that ICT firms generated more patents than non-ICT firms. Many of the ICT firms recognise that R&D activities are plagued by a high risk of failure, uncertainty and asymmetric information. To overcome these market failures, these firms tend to file patents to signal that they have assets in the form of patents/IPs that can be commercialised. Hence, it is not surprising that VC investors prefer investing in ICT-firms with high patent portfolios because these patents can be commercialised even if the firms file for bankruptcy [59]. Increasing digitisation of the economy and demand for new ICT products and services has resulted in the emergence of many start-ups in the ICT industry. This has led to an increase in the flow of VC funding from a wider segment of investors from across the globe to many of ICT developed regions and countries.

3. Methodology

3.1. Hypotheses

Over the last four decades, many countries across the globe have invested significant resources to upgrade their ICT infrastructures and financial systems and to implement economic growth strategies to be globally competitive. One of the major financial reforms that have been undertaken is to provide access to finance for high-risk and technology-intensive firms and start-ups. In this context, many of the countries saw the emergence of vibrant VC industries from the 1980s onwards to support the transformation of all sectors of the economy to become more technology- and knowledge-intensive sectors.

Most of the VC was targeted at developing new technology-intensive sectors that had the potential to raise the productivity and economic potential of the broader economy. These technology-based industries were also envisaged to be new sources of economic growth for many countries.

In this study, we test the following null hypotheses:

H_1^A: Venture capital investment does not Granger-cause per capita economic growth.

H_2^A: Per capita economic growth does not Granger-cause venture capital investment.

H_1^B: ICT infrastructure development does not Granger-cause per capita economic growth.

H_2^B: Per capita economic growth does not Granger-cause ICT infrastructure development.

H_1^C: Venture capital investment does not Granger-cause ICT infrastructure development.

H_2^C: ICT infrastructure development does not Granger-cause venture capital investment.

These hypotheses are summarized in Fig. 1.

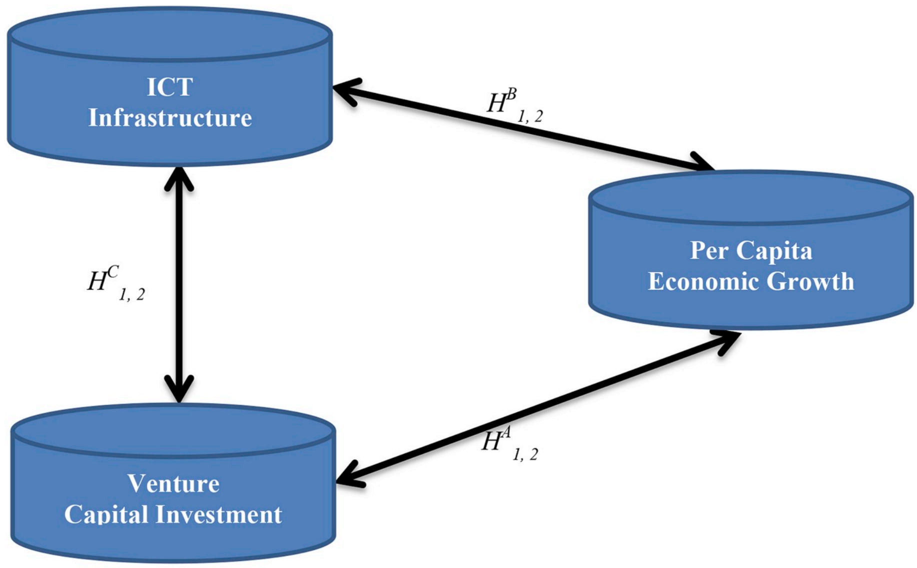

Fig. 1. Possible Causal Relationships among Venture Capital Investment, ICT Infrastructure, and Per Capita Economic Growth.
Note 1: The null hypotheses are:
H_1^A: Venture capital investment does not Granger-cause per capita economic growth.
H_2^A: Per capita economic growth does not Granger-cause venture capital investment.
H_1^B: ICT infrastructure development does not Granger-cause per capita economic growth.
H_2^B: Per capita economic growth does not Granger-cause ICT infrastructure development.
H_1^C: Venture capital investment does not Granger-cause ICT infrastructure development.
H_2^C: ICT infrastructure development does not Granger-cause venture capital investment.
Note 2:
If the null hypotheses are rejected, causality is indicated by the directional arrows that are shown.

***Note 1*:** The null hypotheses are:

H^A_1: Venture capital investment does not Granger-cause per capita economic growth.

H^A_2: Per capita economic growth does not Granger-cause venture capital investment.

H^B_1: ICT infrastructure development does not Granger-cause per capita economic growth.

H^B_2: Per capita economic growth does not Granger-cause ICT infrastructure development.

H^C_1: Venture capital investment does not Granger-cause ICT infrastructure development.

H^C_2: ICT infrastructure development does not Granger-cause venture capital investment.

***Note 2*:**

If the null hypotheses are rejected, causality is indicated by the directional arrows that are shown.

3.2. Data

We utilize annual time series data obtained from *World Development Indicators* published by the World Bank and the European Venture Capital Association's *Venture Capital Database*. We cover 25 European countries,[4] for which data was readily available, from 1989-2016.[5]

We use real per capita economic growth (PEG), which is measured as the percentage change in real per capita GDP, and three different indicators for venture capital investment (VCI). The three VCI indicators[6] are differentiated by the *stage* of the investments and are measured as a percentage of real GDP. Early stage VC investment (VCE) is VC investment aimed towards young businesses that are primarily in their early development stage. Later stage VC investment (VCL) is the type of VC investment aimed at young businesses in need of funds for expansion. Total VC investment (VCT) combines both the early and later stages of VC investment.

We use six different indicators[7] as proxies for ICT infrastructure development: telephone landlines (TEL), mobile phones (MOB), internet users (INU), internet servers (INS), and fixed broadband (FIB). We also use a composite index of ICT infrastructure (CIC[8]), using principal component analysis (PCA) (procedural details are discussed in Ref. [35]. These proxies have been used in several earlier studies such as [32,38]. A more detailed definition of these variables is available in Table A1 under Appendix A.[9]

Our study considers three samples and six cases, where the samples are differentiated by choice of VCI indicator and the cases are determined by choice of ICT indicator. The first sample links VCE, ICT, and PEG, the second links VCL, ICT, and PEG, and the third sample links VCT, ICT, and PEG. In each sample, we consider six cases which differ based on the selection of the ICT indicator (TEL, MOB, INU, INS, FIB, or CIC). The sample size (using various VCI indicators) is not uniform. It

[4] The choice of the European countries was due to the availability of the data to undertake advance panel data analysis for the three variables under study. It was challenging to obtain detailed data for some of the indicators, especially for the venture capital indicators, for countries in other regions.

[5] The countries are Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, Spain, Sweden, Switzerland, and the United Kingdom.

[6] These proxies have been used in earlier studies such as [14].

[7] Each ICT infrastructure indicator is measured ICT use per thousand of population.

[8] CIC is the linear combination of the other five ICT indicators (TEL, MOB, INU, INS, and FIB).

[9] All the variables are converted into their natural logarithms for our empirical investigation process.

Table 1
Panel cointegration test results.

	Case 1 (TEL)		Case 2 (MOB)		Case 3 (INU)		Case 4 (INS)		Case 5 (FIB)		Case 6 (CIC)	
Sample 1: VCE, ICT, PEG												
	Tra	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**	**Tra**	**Max**
None	144*	129*	185*	143*	231*	174*	241*	188*	935*	570*	218*	166*
At most 1	66.5*	59.4*	85.9*	89.8*	122*	92.5*	73.8*	55.4*	106*	78.9*	99.9*	88.7*
At most 2	38.2	38.2	20.6	20.6	71.6*	71.6*	50.0*	50.0*	63.6*	63.6*	50.9*	50.9*
NOC	2		2		3		3		3		3	
Inferences	Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated	
Sample 2: VCL, 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	153*	145*	659*	491*	244*	203*	321*	241*	590*	359*	432*	300.5*
At most 1	38.0	36.4	67.9*	60.5*	87.3*	84.4*	110*	82.5*	119*	118*	70.8*	67.4*
At most 2	27.2	27.2	38.7	38.7	39.0	39.0	61.2*	61.2*	38.4	38.4	35.4	35.4
NOC	1		2		2		3		2		2	
Inferences	Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated	
Sample 3: VCT, 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	150*	161*	188*	151*	228*	172*	291*	259*	590*	448*	183*	134.8*
At most 1	37.8	35.7	78.6*	66.6*	102*	87.2*	93.6*	67.0*	112*	99.2*	87.5*	83.5*
At most 2	27.0	27.0	46.6	46.6	53.0*	53.0*	63.0*	63.0*	52.9*	52.9*	39.8*	39.8*
NOC	1		2		3		3		3		3	
Inferences	Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated		Cointegrated	

Note 1: PEG is per capita economic growth, VCE is venture capital at early stage investment, VCL is venture capital at later stage investment, VCT is venture capital total; TEL is telephone land lines, MOB is mobile phones, INU is internet users, INS is internet servers, FIB is fixed broadband, and CIC is composite index of ICT infrastructure.
Note 2: Tra is trace statistics; Max is maximum Eigen value statistics; and NOC is number of cointegrating vectors.
Note 3: * indicates that test statistics are significant at the 1% level.

varies from case to case depending upon the data availability over the period that is covered. Descriptive statistics (mean, maximum, minimum, standard deviation, skewness and kurtosis) on the variables as well as unit root test statistics are available in Table A2 in Appendix A.

3.3. The econometric methodology

We use the following vector error-correction model (VECM) to investigate the possible directions of causality among our three sets of variables.

$$\begin{bmatrix} \Delta \ln \textit{Venture Capital Investment}_{it} \\ \Delta \ln \textit{ICT Infrastructure}_{it} \\ \Delta \ln \textit{Per Capita Economic Growth}_{it} \end{bmatrix} = \begin{bmatrix} \mu_{1j} \\ \mu_{2j} \\ \mu_{3j} \end{bmatrix} + \sum_{k=1}^{p-1} \Gamma_{ik} \begin{bmatrix} \Delta \ln \textit{Venture Capital Investment}_{it-k} \\ \Delta \ln \textit{ICT Infrastructure}_{it-k} \\ \Delta \ln \textit{Per Capita Economic Growth}_{it-k} \end{bmatrix} + \begin{bmatrix} \lambda_{1i} ECT_{it-1} \\ \lambda_{2i} ECT_{it-1} \\ \lambda_{3i} ECT_{it-1} \end{bmatrix} + \begin{bmatrix} \varepsilon_{1it} \\ \varepsilon_{2it} \\ \varepsilon_{3it} \end{bmatrix} \quad (1)$$

where Δ is the first difference operator; i is the country specification in the panel; t is year; and ε is the uncorrelated error term. Venture capital investment is defined as VCE, VCL, or VCT. ICT infrastructure is defined as TEL, MOB, INU, INS, FIB, or CIC.

The ECT_{it-1} terms are the one-period lag residual of the model (the lagged error-correction terms), obtained from the cointegrating equation that represents the long-run dynamics; while the differenced variables represent the short-run dynamics between the variables. The lagged ECT terms measure the rate by which the long-term disequilibrium in the dependent variable restores back to the equilibrium.

The above model provides robust results if the variables are integrated of order one, I [1], and cointegrated. If the variables used in Eq. (1) are not cointegrated, the ECT_{-1}'s are removed in the estimation process. The directions of causation can be identified by testing the significance of the coefficient of each of the dependent variables in Eq. (1). First, we test the long-run Granger causality by looking at the significance of the speed of adjustment λ, which is the coefficient of the error correction term. The sign of λ should be negative after estimation. The higher the value of λ (in absolute term), the faster is the response of the variable to the previous period's deviations from the long-run equilibrium. The significance of λ indicates the long-run relationship of the cointegrated process, and so movements along this path can be considered permanent. For long-run causality, we test H_0: $\lambda_{ji} = 0$ for $j = 1, 2$, and 3. Next, the study tests the short-run Granger causality test and for this, we test H_0: $\Gamma_{ik} = 0$ for all three variables. Specifically, we are interested in the direction of causality: both directions, from one variable to the other, or no causality.

4. Empirical results and discussion

In panel data analysis, the first step is a panel unit root test to determine the stationarity properties of the relevant variables. We use two panel unit roots, due to [60,61] since no significant evidence of error cross-sectional dependence is found in the data. These tests confirm that all the variables are I [1].[10] These results suggest cointegration between venture capital investment, ICT infrastructure, and per capita economic growth. The Johansen-Fisher Panel cointegration test with an individual intercept is then used to test the hypothesis that there is a long-run relationship between these variables. The results from this test demonstrate the existence of a long-run equilibrium relationship between the three variables in our three samples and six cases (see Table 1).

The above findings support our VECM approach to examine the

[10] The unit root test results are not reported here, but can be available from the authors upon request.

Table 2
Panel Granger causality test results.

Dependent Variable	Independent variables and ECT_{-1}											
Sample 1: VCE, ICT, PEG												
	Case 1 (TEL)				**Case 2 (MOB)**				**Case 3 (INU)**			
	ΔVCE	**ΔTEL**	**ΔPEG**	**ECT_{-1}**	**ΔVCE**	**ΔMOB**	**ΔPEG**	**ECT_{-1}**	**ΔVCE**	**ΔINU**	**ΔPEG**	**ECT_{-1}**
ΔVCE	–	2.22	47.8*	−0.26*	–	3.08	19.1*	−0.01*	–	18.8*	19.4*	−0.04*
ΔICT	8.50*	–	1.54	−0.001	5.29**	–	12.2*	−0.003	1.70	–	4.59***	−0.02
ΔPEG	3.28	7.12*	–	−0.004	2.28	6.52**	–	−0.001	4.98***	2.22	–	−0.001
	Case 4 (INS)				**Case 5 (FIB)**				**Case 6 (CIC)**			
	ΔVCE	**ΔINS**	**ΔPEG**	**ECT_{-1}**	**ΔVCE**	**ΔFIB**	**ΔPEG**	**ECT_{-1}**	**ΔVCE**	**ΔCIC**	**ΔPEG**	**ECT_{-1}**
ΔVCE	–	6.98*	33.2*	−0.29*	–	32.6*	25.2*	−0.32**	–	17.3*	36.7*	−0.24*
ΔICT	10.0*	–	123.0*	−0.002	1.70	–	3.60	−0.004	6.75**	–	3.52	−0.005
ΔPEG	12.7*	64.0*	–	−0.003	1.10	7.76*	–	−0.003	2.07	24.0*	–	−0.002
Sample 2: VCL, ICT, PEG												
	Case 1 (TEL)				**Case 2 (MOB)**				**Case 3 (INU)**			
	ΔVCL	**ΔTEL**	**ΔPEG**	**ECT_{-1}**	**ΔVCL**	**ΔMOB**	**ΔPEG**	**ECT_{-1}**	**ΔVCL**	**ΔINU**	**ΔPEG**	**ECT_{-1}**
ΔVCL	–	5.41**	14.1*	−0.03*	–	11.0*	4.88***	−0.01*	–	12.0*	6.54**	−0.01*
ΔICT	3.37	–	1.15	−0.001	6.02**	–	10.7*	−0.01	12.0*	–	5.10***	−0.01**
ΔPEG	16.9*	8.79*	–	−0.005	10.8*	5.70*	–	−0.14	12.9*	5.13***	–	−0.001**
	Case 4 (INS)				**Case 5 (FIB)**				**Case 6 (CIC)**			
	ΔVCL	**ΔINS**	**ΔPEG**	**ECT_{-1}**	**ΔVCL**	**ΔFIB**	**ΔPEG**	**ECT_{-1}**	**ΔVCL**	**ΔCIC**	**ΔPEG**	**ECT_{-1}**
ΔVCL	–	7.96*	19.1*	−0.034*	–	13.9*	8.07*	−0.04*	–	14.5*	2.98	−0.01*
ΔICT	2.82	–	125.2*	−0.01	5.73***	–	5.29*	−0.02	16.0*	–	3.06	−0.001
ΔPEG	1.58	19.3*	–	−0.03	26.7*	5.80*	–	−0.001	13.6*	21.8*	–	−0.001**
Sample 3: VCT, ICT, PEG												
	Case 1 (TEL)				**Case 2 (MOB)**				**Case 3 (INU)**			
	ΔVCT	**ΔTEL**	**ΔPEG**	**ECT_{-1}**	**ΔVCT**	**ΔMOB**	**ΔPEG**	**ECT_{-1}**	**ΔVCT**	**ΔINU**	**ΔPEG**	**ECT_{-1}**
ΔVCT	–	6.26**	33.0*	−0.16*	–	5.83**	6.44*	−0.001*	–	9.87*	5.04***	−0.01*
ΔICT	9.29*	–	1.54	−0.001	4.06***	–	14.6*	−0.002	6.51*	–	3.11	−0.004
ΔPEG	2.08	13.0*	–	−0.005*	5.65***	6.91**	–	−0.001**	6.07**	1.06	–	−0.001
	Case 4 (INS)				**Case 5 (FIB)**				**Case 6 (CIC)**			
	ΔVCT	**ΔINS**	**ΔPEG**	**ECT_{-1}**	**ΔVCT**	**ΔFIB**	**ΔPEG**	**ECT_{-1}**	**ΔVCT**	**ΔCIC**	**ΔPEG**	**ECT_{-1}**
ΔVCT	–	15.4*	35.1*	−0.19*	–	24.1*	6.22**	−0.12*	–	18.8*	5.04***	−0.01*
ΔICT	1.69	–	142.6*	−0.01	4.85***	–	1.07	−0.014	9.95*	–	5.81**	−0.004
ΔPEG	1.31	47.2*	–	−0.005	6.11**	10.4*	–	−0.001	2.17	31.9*	–	−0.001

Note 1: PEG is per capita economic growth, VCE is venture capital at early stage investment, VCL is venture capital at later stage investment, VCT is venture capital total; and ICT stands for information and communication technology infrastructure and indicates TEL, MOB, INU, INS, FIB, or CIC.
Note 2: TEL is telephone land lines, MOB is mobile phones, INU is internet users, INS is internet servers, FIB is fixed broadband, CIC is a composite index of ICT infrastructure, and $ECT_{-1:}$ lagged error-correction term.
Note 3: *, **, and *** indicate that parameter estimates are significant at 1%, 5%, and 10% levels, respectively.

Granger causal relationships among the variables, the results of which are summarized in Table 2. We first present the long-run results, ascertained by examining the statistical significance of the ECT_{-1} coefficients. Table 2 shows that when ΔVCI[11] is the dependent variable, the lagged ECT coefficients are negative and statistically significant at the 1% level.[12] This confirms the existence of a stable long-run relationship and points to a long-run cointegration relationship between these variables. The lagged ECTs represent the speed of adjustment to restore equilibrium in the dynamic model following a disturbance. The coefficients of the lagged ECTs vary between −0.32 and −0.001, implying that a deviation from the long-run equilibrium following a short-run shock is corrected by about 32%–1% after each year.

Our results in Table 2 also reveal that venture capital investment tends to converge to its long-run equilibrium path in response to changes in ICT infrastructure and per capita economic growth. This is true for all three samples and six cases that we consider. Therefore, the overall conclusion is that venture capital investment in European countries is significantly influenced by both ICT infrastructure and economic growth. In other words, to stimulate long-run venture capital investment, it is important to enhance both ICT infrastructure and economic growth in European countries. Needless to say, smart use of ICT by businesses and strong formation of digital supply chains will increase the demand for new ICT infrastructure, which will help spawn new ICT start-up firms, creating a dynamic and vibrant VC industry in Europe.

Finally, there is some evidence of feedback causality between VCI and economic growth in the long run. This is evident under Sample 2 (Cases 3 and 6) and Sample 3 (Cases 1 and 2). These results show in the long run, economic growth and late-stage venture capital investment have a significant impact on internet usage. Further, internet usage and late-stage venture capital directly influence economic growth in the long run. The VC funding is given to firms after they have commenced commercialisation activities prior to moving to initial public offering (IPO). The late VC funding is normally used to scale-up the firms' operations, including expanding firms' plant and digital capabilities, enabling them to enhance their product quality, market reach, branding and positioning prior to IPO – all of which will contribute to firm performance and contribute to the GDP growth of Europe. These interesting results highlight that the internet is increasingly becoming the backbone of the global supply chain. Hence, the dynamics captured by Sample 2 (Cases 3 and 6) and Sample 3 (Cases 1 and 2) provides further support for the structural changes taking place in the European economies.

[11] VCI is used for VCE, VCL, or VCT.
[12] With one exception (Sample 1, Case 5), where statistical significance is at the 5% level.

Table 3
Summary of short-run Granger causality results.

Short-run Causal Relationships Between				
Samples	Cases	VCI and ICT	VCI and PEG	ICT and PEG
1	**1**	**TEL < = VCE**	**PEG = > VCE**	**PEG < = TEL**
	2	**MOB < = VCE**	**PEG = > VCE**	**PEG < = > MOB**
	3	**INU = > VCE**	**PEG < = > VCE**	**PEG = > INU**
	4	**INS < = > VCE**	**PEG < = > VCE**	**PEG < = > INS**
	5	**FIB = > VCE**	**PEG = > VCE**	**PEG < = FIB**
	6	**CIC < = > VCE**	**PRG = > VCE**	**PEG < =CIC**
2	**1**	**TEL = > VCL**	**PEG < = > VCL**	**PEG < = TEL**
	2	**MOB < = > VCL**	**PEG < = > VCL**	**PEG < = > MOB**
	3	**INU < = > VCL**	**PEG < = > VCL**	**PEG < # > INU**
	4	**INS = > VCL**	**PEG = > VCL**	**PEG < = > INS**
	5	**FIB < = > VCL**	**PEG < = > VCL**	**PEG < = > FIB**
	6	**CIC < = > VCL**	**PEG < =VCL**	**PEG < = CIC**
3	**1**	**TEL < = > VCT**	**PEG = > VCT**	**PEG < = TEL**
	3	**MOB < = > VCT**	**PEG < = > VCT**	**PEG < = > MOB**
	3	**INU < = > VCT**	**PEG < = > VCT**	**PEG < # > INU**
	4	**INS = > VCT**	**PEG = > VCT**	**PEG < = > INS**
	5	**FIB < = > VCT**	**PEG < = > VCT**	**PEG < = FIB**
	6	**CIC < = > VCT**	**PEG = > VCT**	**PEG < = > CIC**

Note 1: PEG is per capita economic growth, VCE is venture capital at early stage investment, VCL is venture capital at later stage investment, VCT is venture capital total; TEL is telephone land lines, MOB is mobile phones, INU is internet users, INS is internet servers, FIB is fixed broadband, and CIC is composite index of ICT infrastructure.
Note 2: VCI stands for venture capital investment and indicates VCE, VCL, or VCT.
Note 3: ICT stands for information and communication technology infrastructure and indicates TEL, MOB, INU, INS, FIB, or CIC.
Note 4: < = / = > / < = > indicate the direction of Granger causality; and < # > indicates no causality.

In the short run, the results are mostly non-uniform, with two exceptions: we found unidirectional causality from telephone landlines to economic growth and the bidirectional causality between the composite index of ICT infrastructure and venture capital investment. We summarize the *non-uniform* short-run results in Table 3, demonstrating that the short-run adjustment dynamics vary across samples/cases. The details of these results are presented below.

Hypothesis 1. ($H_{1,\ 2}^{A}$) contends that the venture capital investment Granger-causes economic growth, and vice versa. We find mixed short-run results regarding this hypothesis. With Cases 1, 2, 5, and 6 (in Sample 1: VCE), Cases 4 and 6 (in Sample 2: VCL), and Cases 1, 3, and 6 (in Sample 3: VCT), we find unidirectional causality between per capita economic growth and venture capital investment. Conversely, we find bidirectional causality between per capita economic growth and venture capital investment with Cases 3 and 4 (in Sample 1), Cases 1, 2, 3, and 5 (in Sample 2), and Cases 2, 3 and 5 (in Sample 3).

Hypothesis 2. ($H_{1,\ 2}^{A}$) contends that ICT infrastructure Granger-causes per capita economic growth, and vice versa. We also find mixed short-run evidence regarding this hypothesis. With Cases 1, 3, 5, and 6 (in Sample 1: VCE), Cases 1 and 6 (in Sample 2: VCL), and Cases 1 and 5 (in Sample 3: VCT), we find unidirectional causality between per capita economic growth and venture capital investment. We find bidirectional causality between per capita economic growth and venture capital investment with Cases 2 and 4 (in Sample 1), Cases 2, 4, and 5 (in Sample 2), and Cases 2, 4 and 6 (in Sample 3). We also find the evidence of neutrality in a few cases, such as Case 3 in both Samples 2 and 3.

Hypothesis 3. ($H_{1,\ 2}^{A}$) posits that venture capital investment Granger-causes ICT infrastructure, and vice versa. As with the other two hypotheses, short-run causality results here are mixed. With Cases 1, 2, 3, and 5 (in Sample 1: VCE), Cases 1 and 4 (in Sample 2: VCL), and Case 4 (in Sample 3: VCT), we find unidirectional causality between venture capital investment and ICT infrastructure. On the contrary, the study finds bidirectional causality between ICT infrastructure and venture capital investment with Cases 4 and 6 (in Sample 1), Cases 2, 3, 5, and 6 (in Sample 2), and Cases 1, 2, 3, 5 and 6 (in Sample 3).

The discussions above show that the development of the digital economy in Europe opens up new opportunities for firms to enhance their productivity and economic performance, fuelling the demand for VC funding. On the other hand, the strong economic growth potential of the firms and access to VC funding will enable firms to adopt new business models underpinned by advanced ICT infrastructure and systems. This will increase the demand for and contribute to the development of ICT infrastructure. The results show that the impacts of ICT, venture capital funding and economic growth reinforce and deepen one another – all of which are critical for the sustained economic performance of in 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 the variables. Hence, careful curation of policies to develop the ICT infrastructure and adoption rates, the establishment of a vibrant VC industry, and implementation of economic growth promoting strategies must take into consideration the 'spill-over' impacts these policies have on the digital and VC ecosystems and GDP growth in Europe.

5. Hypotheses validation and limitations of the study

To supplement our analysis, some additional estimations were performed. The analyses and results, though not reported here because of space constraints,[13] deserve a brief mention. First, the FMOLS[14] and DOLS[15] were used to capture the dynamics between venture capital investment, ICT infrastructure, and economic growth. Second, a

[13] All of the results from additional estimations are available from the authors upon request.

[14] FMOLS is fully modified ordinary least squares (OLS), a non-parametric estimation approach, which takes 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 (see, for instance, Maeso-Fernandez et al., 2006; 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 (see, for instance, Kao and Chiang, 2000).

sensitivity analysis was performed by changing the order of the vector error-correction model. Third, Generalised Impulse Response Functions (GIRFs) were used to gain additional insights into how the shocks to the variables impact the other variables. These additional estimation results generally support our earlier overall findings. In particular, the results from our sensitivity analysis did not present a substantial change to our earlier main findings.

Nonetheless, a brief discussion of some of the limitations of our study is in order. First, while the deployment of VECM is an appropriate methodology, our study has not considered non-linearity tests and/or structural breaks, which may lead to biases in the results. Second, our study could not incorporate some of the other ICT indicators like the internet of things (IoT) and usage of other ICT devices due to the lack of available data over the sample period for the European countries.

6. Policy implication and concluding remarks

This study uses advanced statistical techniques to study the complex short-term and long-term relationships between venture capital investment, ICT infrastructure, and economic growth simultaneously in Europe. In doing so, we integrate three strands of the literature, which examine the link between two of these variables at a time. The empirical analysis shows that the three variables are cointegrated. Most importantly, there is clear evidence that both ICT infrastructure and economic growth matter in the determination of long-run venture capital investment. In the short term, the results also show that in most cases, the development of ICT infrastructure, VC industry, and economic growth deepen and reinforce one another. These empirical results confirm the view expressed by policymakers and industry experts that the formation of digital supply chains and the development of new business models using the digital platforms will create a vibrant VC industry and spur economic growth in Europe [62,63]; and [64].

The empirical results also suggest that in order to stimulate sustained economic growth in the European economies, policy-makers should give careful thought to the inter-dependence of the various policy measures pertaining to the development of ICT, the VC industry, and economic growth. Key policies related to ICT infrastructure development, the creation of a vibrant VC industry, and development of a sound economic ecosystem in Europe are outlined below.

First, priority should be given to putting in place a systematic framework in Europe to continuously develop and upgrade the ICT infrastructure so as to ensure that firms have access to state-of-the-art ICT infrastructure. This will enable them to enhance their reach for resources, knowledge and markets, and assist them in improving the quality of their products and services. The ICT strategy should also incorporate the development of user-friendly and affordable technology and applications for consumers to use the digital platforms to gain access to new products and services.

Greater adoption of ICT will also be reinforced by facilitating affordable ICT literacy programs and strengthening the digital regulatory architecture to mitigate risks associated with cybercrimes. Various programs have been introduced by some of the countries in Europe to raise the firms' ICT skills, especially SMEs. Among them are the following: peer-to-peer digital skill programs; mentorship of SME's by larger and well-established corporations; access to ICT skills training programs from vocational institutes, colleges and institutions of higher learning; and online ICT skills training programs. In this context, the introduction of the *European e-Business Network,* which helps strengthen ICT education and the digital supply chain for e-business, is a positive step towards promoting digital entrepreneurship and economic growth among the SMEs in Europe [65]. Further, the establishment of the European Cybercrime Centre, which helps monitor and put in place measures to address cybercrime, cybersecurity and data privacy, has played a key role in enhancing business and consumer confidence, which will likely increase the use of digital platforms by all stakeholders [66].

The second priority is to pursue GDP growth-promoting strategies, which include creating appropriate incentives to increase domestic and foreign investments into the European economies, especially in the ICT-driven industries. These investments are important for developing the ICT infrastructure, increasing the supply of ICT-savvy workforces and strengthening the VC industry in Europe. Among the key business-friendly policies are the following: removal of barriers that hinder digital entrepreneurship; regulatory reforms to harmonise legislations, laws and business practises among the diverse member countries in Europe; and mobilisation of resources to nurture vibrant start-up ecosystems, incubators, and accelerators that foster e-governance, digital innovation and job creation in Europe [62,65].

The third priority is to foster strong and vibrant VC ecosystems in Europe, which will not only create employment but also spawn new technology start-ups that will lead to the development of next-generation competitive industries. Among the major challenges faced by the European VC industry are the following: lack of harmonisation of regulatory and financial systems in member countries; low economic growth potential in many of the developing economies in Europe; and low levels of private and institutional investors [2]. Strengthening and harmonising the financial regulations, increasing digital entrepreneurship, and developing strong digital supply chains will be important drivers for increasing promising business ventures in the less developed or emerging regions of Europe – all of which, will result in stronger and more dynamic VC industries across Europe.

In summary, this study highlights the strong interdependence between the ICT infrastructure, venture capital, and economic growth, both in the short run and long run, in Europe. These results suggest that policymakers in the region should take an integrated approach to capture the positive externalities of the policy intervention strategies pertaining to the creation of a sound digital economy and a vibrant VC industry to ensure sustainable economic growth in Europe. Lessons from this European case study provide valuable insights for policymakers in other regions on co-development strategies pertaining to the development of ICT infrastructure, the VC industry and other economic growth promoting initiatives.

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Appendix A. Variables

Table A.1
Definition of Variables.

Variables' Code	Variables' Definition
SET 1: VENTURE CAPITAL INVESTMENT INDICATORS	
VCE	**Venture capital investment at an early stage:** venture capital investment aimed at young businesses in their primary development stage. This is expressed as a percentage of gross domestic product (GDP).
VCL	**Venture capital investment at a later stage:** venture capital investment aimed at young businesses in need of expansion capital (as a percentage of GDP).
VCT	**Total venture capital investment:** venture capital investment directed at both early stage and later stages (as a percentage of GDP).
SET 2: ICT DEVELOPMENT 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 infrastructure**: this is the weighted average of TEL, MOB, INU, INS, and FIB.
SET 3: ECONOMIC GROWTH INDICATOR	
PEG	**Per capita economic growth**: Calculated as a percentage change in per capita GDP.

Note 1: Variables above are defined in the *World Development Indicators* of the World Bank and the European Venture Capital Association's *Venture Capital Database*.
Note 2: All monetary variables are measured in constant US dollars.
Note 3: Natural logarithm of the variables are used in the estimation process.

Table A.2
Descriptive Statistics and Unit Root Statistics.

Variable	Descriptive Statistics	Unit Root Statistics							
	Mea	Max	Min	Std	Ske	Kur	LLC	IPS	Inference
VCE	1.383	3.627	−5.586	1.552	−2.687	10.22	−3.663*	−6.796*	I [1]
VCL	1.503	3.886	−5.075	1.622	−2.564	9.975	−3.960*	−8.678*	I [1]
VCT	1.936	4.077	−2.959	1.138	−1.974	7.655	−7.924*	−9.121*	I [1]
TEL	2.623	2.871	1.991	0.149	−1.150	4.757	−3.200*	−2.816*	I [1]
MOB	3.036	3.236	2.239	0.111	−2.358	15.68	−3.356*	−4.609*	I [1]
INU	2.794	2.988	1.657	0.188	−2.042	9.192	−8.603*	−7.296*	I [1]
INS	−0.535	0.492	−2.622	0.633	−0.607	2.950	−4.560*	−2.990*	I [1]
FIB	2.203	2.652	−0.567	0.514	−2.742	11.97	−33.30*	−18.20*	I [1]
CIC	0.548	0.803	−0.332	0.166	1.373	6.251	−4.191*	−2.537*	I [1]
PEG	1.675	1.855	1.572	0.028	0.730	9.735	−41.90*	−49.70*	I [1]

Note 1: VCE is venture capital at early stage investment, VCL is venture capital at later stage investment, VCT is venture capital total investment, TEL is telephone land lines, MOB is mobile phones, INU is internet users, INS is internet servers, FIB is fixed broadband, CIC is a composite index of ICT infrastructure, and PEG is per capita economic growth.
Note 2: Mea is mean, Max is maximum, Min is minimum, Std is standard deviation, Ske is skewness, and Kur is Kurtosis.
Note 3: Log-transformed values for the variables are reported in this table.
Note 4: LLC is Levin-Lin-Chu statistics, and IPS is Im-Pesaran-Shin statistics. Both these statistics are reported here at first difference level only. I [1] denotes integration of order one.
Note 5: * indicates significance at the 1% level.

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