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Innovation in Venture-Capital Backed Clean-Technology Firms in the UK

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Innovation in Venture-Capital Backed Clean-Technology Firms in the UK

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This paper studies the relationship between innovation and venture capital (VC) funding for a sample of 239 UK firms active in the clean technology sector (cleantech) using a unique combination of three datasets; (1) FAME, (2) UK Intellectual Property Office patent data and (3) Cleantech Network's Venture Investments data. Cleantech, a relatively new investor defined term, covers a range of different applications broadly aimed at alternative energy production or providing solutions to environmental problems (Cooke, 2008). However, as investors are generally motivated by financial return, rather than environmental solutions we use this paper to understand the relationship between cleantech investment, technology innovation and the role of different types of investor. We profile the VC-backed firm's active in clean technologies across UK sectors and investigate the relationship between venture capital, investor specialization and experience, and the patenting activities of these firms.

The paper is motivated by the observation that innovation in clean technologies has gained momentum since 1980s with the growing political emphasis on sustainable economic development. The UK has risen as one of the most innovative countries in clean technologies starting from 2000 despite its role as a laggard in early 1990s (Martin and Wagner, 2009). Venture capital is recognized as important for supporting new technology innovations (Lerner and Gompers, 2001). However, not all investors perceive opportunities in the same way (Dimov and Milanov, 2009) and specialization and experience play an important role in selecting the right deals (Gupta and Sapienza, 1992; Gompers et al, 2009).

In this paper we look at the different technology foci and investment roles of investors active in cleantech. We seek to understand whether investors specialize in particular technology areas, and the role of specialists in the staging of cleantech deals. Finally we consider whether specialization is related to investments involving new innovation, as measured by patents classified according to International Patent Classes.

Innovation in Venture-Capital Backed Clean-Technology Firms in the UK

1 Introduction

The provision of risk capital funding for start-up business is considered an important requirement for developing and supporting entrepreneurial firms. However, the expected role of the venture capitalist goes beyond the provision of funding, particularly in the US, where VC provide both financial and business support to entrepreneurial firms. In this paper we make an initial investigation of the relationship between venture capital and UK firms in the emerging clean technology sector. To our knowledge little academic research has examined the underlying innovative behaviour of cleantech firms funded by venture capitalists. This paper uses patent data as an indicator of innovative activity to assess the innovation and finance relationship.

The development of modern forms of venture capital investment and its evolution away from the United States has been well documented (Bygrave and Timmons, 1992; Gompers and Lerner, 1999). During recent decades, the availability of this form of financing has grown rapidly, driven by the demand for equity based finance from entrepreneurial businesses in regions with a strong technology focus, such as Silicon Valley or Cambridge (UK). In the UK the supply of venture capital investment has been encouraged as a means of supporting the rapid development of new entrepreneurial ventures, effectively using investment and entrepreneurial expertise to shorten the time it takes to get a product to market. However the UK Venture capital industry has frequently been criticised for failing to support early stage companies, preferring to invest larger amounts in more established companies.

The Clean-Technology sector, or cleantech, as it is commonly referred to, is a sector that has gained increasing investor activity over the last few years. Although a commonly used investor term, the sector is comprised of a wide range of technology covering a variety of applications. Thus our approach is to investigate the development of the industry, which is heavily supported by venture capital activity, to understand the relationship between the source of finance and underlying development of the technology.

Venture capital is synonymous with the concept of innovation. However, in cases where innovation involves significant development times it may not necessarily 'fit' within the usual five or ten year venture fund timelines. Likewise, evidence also demonstrates that new innovative opportunities can lead to financial investment bubble, which has mixed implications for the development of the underlying innovation, for example research by Deutsche Bank (2010) suggests venture capital investment in the energy sector is closely tied to increases in crude oil prices. This raises several important questions – To what extent do venture capitalists support innovative firms as opposed to concentrating on short-term commercial returns in the cleantech sector? Are clean-tech investors specialised and what implications does venture capital finance have on the firm level innovation processes and outcomes?

In the next section we explore these questions using the literature. We start by providing a background of investment in the UK cleantech sector which provides the motivation for the paper. Next we briefly review a general model for venture capital, and explore a scattered literature describing the development of the clean-technology landscape in relation to the technology and investment patterns. Next we examine the literature evaluating the impact of venture capital on patenting – a key indicator of innovative output. Then, we look at the influence of venture capital on firm R&D activity, specifically looking at R&D make or buy decisions and R&D investment.

2 Innovation and venture capital funding trends in the UK cleantech sector

Technology and radical innovation will play an important role in meeting the resource demands of economic development whilst minimising its environmental impacts (Bosetti et al 2009). An awareness of the need for new sustainable and environmental technologies has grown since the 1970s (Shrivastava, 1995) but investment into developing new clean and environmental innovation has been limited. More recently evidence suggests that technologies in the renewable sector are gaining acceptance with double digit growth in some energy sectors (Jacobsson and Johnson, 2000). However progress towards changing the energy system overall has generally been slow and uncertain (Jacobsson and Johnson, 2000).

The paper is motivated by the observation that innovation in clean technologies has gained momentum since 1980s with the growing political emphasis on sustainable economic development. The UK has risen as one of the most innovative countries in clean technologies starting from 2000 despite its role as a laggard in early 1990s (Martin and Wagner, 2009). While there are noteworthy studies that examine UK innovations in clean technologies and the determinants of these innovations (Green et al., 1994; Klaassen et al., 2005); the literature has not specifically explored the activities and the innovative potential of promising UK cleantech firms that have qualified to receive VC funding. Likewise, the role of VC funding in promoting clean technology innovations is not an area that has attracted attention in either of the current innovation or VC literatures.

Cleantech is a relatively new investor-defined term that covers a range of different applications broadly aimed at alternative energy production or providing solutions to environmental problems (Cooke, 2008). Cleantech Networks (2009) describe the cleantech as, “new technology and related business models that offer competitive returns for investors and customers while providing solutions to global challenges”, involving products and services associated with “providing superior performance at lower costs” reducing ecological impacts and more productive use of natural resources. Although, a widely used term to raise new investment funds (BVCA, 2009), the cleantech sector is still at very early stages of its evolution and it is less clear to what extent it can be presented as an integrated sector of activity. It covers a range of different technologies, such as solar, nuclear, wind and marine energy generation; the production of low carbon fuels, buildings, vehicles and electronics, as well as efficient technologies related to traditional oil derived fuels (BIS, 2009).

Investments in cleantech infrastructure and R&D have increased in response to government commitments to cut down the carbon emissions by around one-third by 2020. The UK government, for example, allocated a sum of £405 million towards this cause in 2009 (The UK Department of Energy and Climate Change, 2009). In line with the increased investments, Thomson-Reuters (2009) indicates that the level of global patenting increased by threefold in the solar, wind and marine technology areas comparing the periods of 1997-1999 and 2006-2009 across various countries. The analysis indicates the marine technology dominates over solar and wind in the UK, in contrast to other countries, such as Germany and China, which specialize in solar energy, or alternatively Japan which specializes in wind related innovation.

According to the findings of the Thomson-Reuters (2009), the UK cleantech innovation appears to be reliant on smaller firms and contributions from the academic sector. In contrast to most other countries, large UK firms do not appear to be as active in patenting clean technologies. More importantly, a recent study suggests that the cleantech ideas patented by large multinational firms have on average taken 24 years to reach the mass market- a far too lengthy time period in the shadow of climate change and the predicted increases in global temperatures (Chatham House Report, 2009).

The innovative advantages of small firms is well documented especially in the early stages of new industries during which the innovations are more radical and innovative activities are distributed across a wide population of firms (Abernathy and Utterback, 1978; Agarwal and Gort, 1996; Gort and Klepper, 1982; Klepper, 1996, 1997;). In general, small firms tend to concentrate on technologically “diverse and un-crowded territories”, while large firms work on “more mature” technologies (Fauchart and Keilbach, 2002, p.2). In the words of Freeman and Soete (1999) “... small firms may have some comparative advantage in the earlier stages of the inventive work and the less expensive but more radical innovations…” (p.234).

Thus, our focus on the SME activity is well positioned and timely for understanding the early stage innovation dynamics in the UK cleantech sector. While large firms come under pressure to gradually cut down their environmental impact through abatement activities which are often classified as process innovations, smaller firms have the incentive to specialize in radical cleantech product innovations in an attempt to gain entry into the market.

In the cleantech sector, the recent rise of innovative activity and the increased perception of commercial prospects have drawn investors towards supporting smaller innovative cleantech firms. For example, Cleantech Network (2008) reports that venture capital investment in North America, Europe, Israel and China have increased from $500 million in 2001 to $8000 million in 2008. A recent survey of investor attitudes by Deloitte Touche Tohmatsu (2009), found that 60% of investors expected to increase their exposure to cleantech investment in the next three years. Cleantech has become one of the most important VC investment sectors, following the biotechnology and IT sectors (Cleantech Network, 2009)

In the UK, in the face of declining venture capital activity across sectors, members of the British Venture Capital Association (BVCA) increased cleantech investment to £1.3 billion in 2008. A detailed breakdown of the VC investment activity by primary cleantech industry over the years can be found in Table 1. The UK government also recognizes the need to maintain an economic environment favourable to entrepreneurship in the cleantech sector and has already taken a proactive step to stimulate the supply of venture capital to the low carbon energy sector through several public initiatives such as the newly introduced Energy Technologies Institute (www.energytechnologies.co.uk).

Table 1: Deal value by year and primary industry ($m)

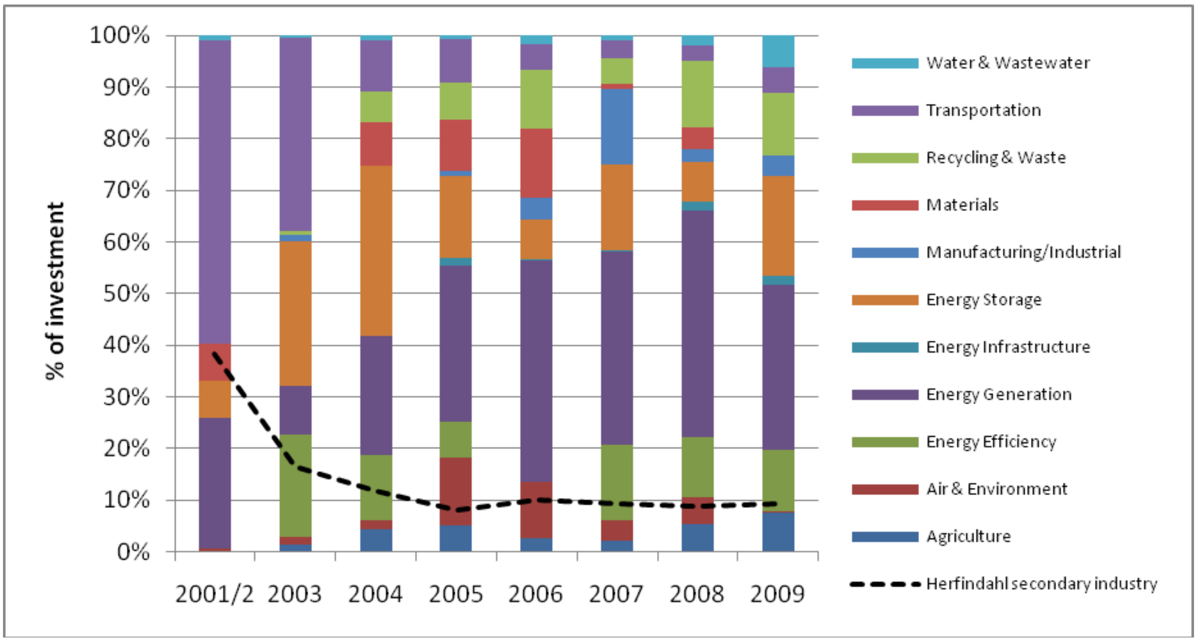
	Deal year								
Primary Industry	2001/2	2003	2004	2005	2006	2007	2008	2009	Total
Agriculture	0.0	1.2	5.7	13.0	5.0	8.2	18.7	17.3	69.1
Air & Environment	0.5	1.4	2.2	33.2	20.8	15.5	18.4	0.7	92.6
Energy Efficiency	0.0	18.4	16.3	17.7	0.0	55.5	40.5	27.6	175.9
Energy Generation	21.0	8.7	29.5	76.5	81.4	143.2	153.3	73.8	587.3
Energy Infrastructure	0.0	0.0	0.0	3.7	0.5	1.2	6.5	4.0	15.9
Energy Storage	6.1	26.0	42.5	39.7	14.3	63.6	27.0	44.2	263.3
Manufacturing/Industrial	0.0	1.1	0.0	2.5	8.3	56.2	8.5	9.6	86.1
Materials	6.0	0.0	11.0	25.3	25.3	4.1	14.4	0.0	86.1
Recycling & Waste	0.0	0.8	7.7	18.3	21.5	18.8	44.8	27.6	139.5
Transportation	48.8	34.5	12.8	21.1	9.7	13.1	11.0	11.8	162.7
Water & Wastewater	0.8	0.5	1.1	1.8	3.2	3.8	6.6	14.1	31.9
Grand Total	83.2	92.6	128.7	252.7	189.9	383.0	349.6	230.8	1710.5

Source: CleanTech Network, collated by authors.

Based on Table 1, energy generation, storage and efficiency are the leading areas of investment activity in the UK, taking a total of $1027m during the period analyzed. Figure 1 shows the breakdown of the shares of investment over the years. Comparing the activity of different primary industries throughout the period shows, that no single investment area has maintained priority. Figure 1 shows applications in transportation and energy storage have given way to investment in energy generation. Other primary industry application areas have shown a mixed trend of activity between 2001 and 2009; applications in recycling, air and environment, and water show a volatile trend in their share of investment activity.

Figure 1 also plots the herfindahl concentration ratio based on investment activity across 34 secondary industries during the period. The general trend has been a diffusion of investment across industries with time, such that even within a particular primary industry an increasing variety of applications compete for funding.

Figure 1: Shares of investment value and herfindahl index investment concentration



The BVCA governing board recently reported that 'The environmental, social and governance agenda and PE [Private Equity] Houses' profit motives are certainly not mutually exclusive"[1] (BVCA, 2008) suggesting a role for BVCA members in supporting environmental technologies with social benefits. However, it is important to explore the role and efficiency of venture capital funding in supporting high quality radical clean technology innovations. The risks resulting from investing in new technology in an emerging industry may be too large for many venture capitalists, and may restrict the development of the most radical and urgently needed innovations. Understanding which types of innovations and innovators are targeted by VC investors will help to identify areas of market failure and hence highlight other areas that require non-VC type innovation funding.

[1] Statement from Wol Kolade, Chairman of the BVCA responsible investment board.

2.1 The model of venture capital operation

A basic model for operating a venture capital company is largely accepted in the literature. Its historical development, processes and examples of successes and failures, have been provided by Florida and Kenney (1988), Sahlman (1990), Bygrave and Timmons (1992). More recently Gompers and Lerner (2001) have provided a detailed review of the "Venture Capital cycle". All these studies pertain to the evolution of this model in the United States.

Venture capital is a form of finance specifically aimed at growing businesses by providing financial investment and additional business support services. Only certain business opportunities are suitable for venture capital investment. Typically businesses which obtain funding from venture capitalists are expected to grow rapidly and have the potential to provide significant return on investment. However, the venture capital cycle is very risky. On average only two out of ten investments will meet the original expectations of the venture capitalist and many investments make a loss (Bygrave and Timmons, 1992).

The focus of venture capitalist activities are in the initial 7-10 years of the technology cycle, which starts with the inception of the company and plots its development through the stages of emergence and consolidation (Florida and Kenney, 1988). The venture capital cycle starts with a phase of due diligence to assess the investment opportunity. If a decision to invest is made, finance is provided to the company in return for partial ownership and control. The venture capitalist usually takes equity in the company and often reserves the various controlling rights including a position on the firm's board of directors. Venture capitalists realise the growth in the value of their investment by exiting through public stock markets via initial public offerings (IPO), or through the sale of their equity to another company, known as a trade sale (Gompers and Lerner, 2001).

Usually, a venture capital investment is followed by an intensive effort by the entrepreneurial team and investors to accelerate development of the company through the technology cycle.

In addition to providing finance, the venture capitalist is also expected to take an active involvement in managing firms. This can include providing guidance and assistance on business strategy, access to various business and technology networks, and if necessary recruiting the necessary senior management to develop the firm (Florida and Kenney, 1988). Over the lifetime of an investment, the role of the venture capitalist moves from entrepreneurial support, to more traditional management and marketing inputs, associated with established companies.

For the economy and industry as a whole, venture capital thus assumes an intermediary function between financiers and industry that utilises “overlapping networks” for raising finance, performing due diligence and maintaining the internal resources of the venture capital company itself. Florida and Kenney (1988) suggest that the role of the venture capitalist is to accelerate the speed of technology change, whilst taking on a “technological gate keeping role” (p.125).

2.2 Venture capital, patenting and the technology dynamic

Venture capital has become an important part of the technological entrepreneurship mechanism, providing risk capital to innovative new projects (Florida and Kenney, 1988; Bygrave and Timmons, 1992; Etzkowitz, 2005; Pisano, 2006). The high risks, long development times and significant costs of innovation often make traditional forms of finance inappropriate. Venture capitalists are expected to have a unique view of the industry with experience in understanding what makes a successful firm (Pisano, 2006). They develop capabilities that allow them to invest in and manage opportunities that provide an appropriate commercial risk to return balance.

Venture capital is expected to be more than finance, playing a strategic role in guiding the development of the firm. The venture capitalist is expected to be an important agent in the interactions and relationships developed by firms, helping in the transition of an R&D based firm from a collection of scientific knowledge assets, to a functioning firm that can demonstrate its potential to the wider financial community (Niosi, 2003). In this role the VC can also help support internal firm capabilities by bringing external resources and competences into the firm. VC have been described as providing a vital coaching role for new entrepreneurs (Hellmann and Puri, 2002), or access to important entrepreneurial knowledge, networks and contacts to support the development of start-up firms (Zook, 2002, 2004).

In high-tech industries such as the biotech industry, the venture capitalist operates to "facilitate commercialisation" of new knowledge, by providing finance and the strategic knowledge of how to reach the market (Cooke, 2003). Niosi (2003, p.749) sees a clear commercialisation route for spinout firms, where patents, collaborations with large firms and venture capital are key,

"The sequence starts with obtaining patents. These will signal to the financial community the value of the new firm. Patenting is followed by venture capital, entry into the stock market under the guidance of the venture capital firm, and the organisation of a major alliance followed by the launching of the firms products in overseas markets, usually with the help of large international corporate partners."

However, such a sequence should not necessarily assume all VC's are similar. The transition of venture capital from the US has seen a greater emphasis of late stage investment emphasising lower innovation risk and greater financial engineering as opposed to more patient 'hands on' investment (Bygrave and Timmons, 1992, Mason and Harrison, 2002). It follows that not all investors perceive opportunities in the same way (Dimov and Milanov, 2009) and specialization and experience play an important role in selecting the right deals (Gupta and Sapienza, 1992; Gompers et al, 2009).

In addition, investing in R&D intensive firms is expensive, for example Hall (2002) found that around 50% of the R&D expenditure was on staff costs in R&D intensive firms. The high risk high cash burn nature of R&D can often only partially be matched by venture capital (Hall, 2002) and might suggest VC should reduce their exposure to the highest risk projects. On the other hand, Hall (1992) finds firms receiving other types of finance, such as debt finance, are not associated with R&D intensive activity. Champenois et al. (2006) finds venture capital closely associated with the highest risk projects in German biotech firms, whilst lower risk projects, such as service or supplier based business were favoured by corporate investors, looking to support their own product portfolio development or strengthen supply chains. In Champenois et al (2006) only firms involved in developing products (i.e. firms classified as highest risk) received investment from venture capitalists. Thus, whilst venture capitalists are associated with high risk R&D intensive firms, the literature describes a balance between the need to develop innovation with achieving short term returns.

For the venture capitalist, one of the primary motivations for investing in high risk technology is the size of the expected return, when, for example, large institutional investors are prepared to buy shares in the company. The public flotation of a firm provides the opportunity for the venture capitalist to sell their equity in the company and realise the growth in its value (Pisano, 2006). However, from Niosi (2003) we see that venture capitalists are active after initial innovative effort has occurred. The investor's motivation is to build the firm to achieve entry onto the stock market, or sale to a larger company.

It is not surprising therefore that the history of venture capital is closely related to the exploitation of technology bubbles, for example during the Internet and biotech bubble venture capital investment increase rapidly, associated with the entry of novice investors, such that many firms without the necessary technological and innovative capabilities received funding and failed to produce the required return. More generally Pisano (2006) indicates that returns from the biotech industry are not commensurate with the level of risk involved in early stage investing vis-à-vis investing in public stock and suggests investors' short term focus may lead to suboptimal returns. In fact Kedrosky (2009) believes that the recent poor level of industry return in venture capital is symptomatic of a lack of new innovative opportunities in the traditional biotech and IT investment areas. This has also led recent industry commentators to link the cleantech sector to the next venture capital bubble (Lux Research, 2007).

However, Aghion et al (2009) believe there is a lack of innovation in green technologies. They measured patenting activity and the level of public investment in R&D in green technologies finding only a small proportion of total national innovative activity is related to the environmental sector, a finding which holds across many innovative countries. According to Aghion et al (2009) a lack of public investment and decisive policy direction has failed to create the conditions necessary to kick start the private sector.

Our discussion above raises important questions as to whether venture capital will support innovation in the cleantech industry. In the next section we review literature analysing the impact of venture capital on innovation as measured by patenting activity.

2.3 The impact of venture capital on patenting

Patenting is a widely used measure of innovation, capturing firm's attempts to build monopoly profits from their new invention. Kortum and Lerner's (2000) extensively cited research paper uses an industry analysis of R&D and patenting activity in the US to show that venture capital investment was more productive than corporate R&D in producing patents. They found, on average, VC accounted for approximately 8% of industrial innovation between 1983 and1992, based on the equivalent of 3% of total corporate R&D (or that VC is 3 times more effective at stimulating patents than corporate R&D). Ueda and Hirukawa (2008) support the Kortum and Lerner (2000) conclusions, finding that the relationship between venture capital and innovation strengthens during the 1990s, when the venture capital industry was expanding rapidly. The authors also find venture capital is associated with firms that have more original patents, as measured by the technical breath of the patents being cited in an application, indicating venture capital is used to finance more radical innovation.

In Germany Engel and Keilbach (2007) studied the patenting activity of SME using a matched sample of VC and non-VC funded firms concludes that VC funded firms grow faster than non-VC funded firms, but that differences in patenting activity relate most strong to the period prior to investment. Engel and Keilbach (2007) suggest that venture capital investors are focused on the commercialization of existing innovation, rather than the innovative effort or the downstream innovation process. Engel and Keilbach (2007) conclude that VC's identify the high growth potential firms prior to making an investment. Hirukawa and Ueda (2008) also identify evidence that venture capital follows innovation, but find little evidence of any causal relationship between venture capital and patenting activity. However, they extend their analysis by investigating the relationship of patenting with first and follow-on rounds to show that the lagged influence of venture capital is to reduce patenting activity. Thus the authors suggest their findings support the view that venture capital results in a reduction of patent applications for firms that were already patenting.

2.4 The impact of venture capital on firm research strategy

Broadly the literature concludes that venture capital is supportive of innovation within firms. Hellman and Puri (2000) study of Silicon Valley firm's finds innovators are more likely to receive venture capital, and also quicker take a product to market. Da Rin and Penas (2007) study the effect of venture capital on innovation strategies using data from the CIS Innovation survey in the Netherlands. The paper categorizes the R&D strategy using a matrix of 'Buy R&D' / 'Make R&D' / 'Buy know-how' decisions and their combinations. Da Rin and Penas

(2007) conclude, after controlling for firm characteristics, that VC is most strongly related firm R&D strategies involving make and buy, as opposed to only buy or only make strategy. In their view this supports the role of VC in developing absorptive capacity in VC backed firms, which was also confirmed by their results showing the role of VC in supporting selective persistent R&D activity. In contrast public funding increased the likelihood of all types of innovation and is not selective.

3 Empirical approach

The literature finds that venture capital is broadly supportive of innovation, but is motivated to commercialise, rather than fund basic research. In some high-tech sectors patents have been shown to be a key signal in the investment process, confirming that investors provide funding to innovative firms. However, for innovation at a very early stage, obtaining funding maybe more difficult, particularly in the UK with fewer investors prepared to commit significant funding prior to obtaining a patent or demonstration of proof of concept.

In the absence of previous research examining the relationship between cleantech innovation and venture capital funding we use our discussion of the literature to guide an exploration of the cleantech sector to understand whether investors have specialised in funding innovative firms. Firstly, we look the technology fields where venture capital has supported patenting firms, specifically concentrating on higher quality innovations (i.e. those with multiple citations). We then use innovative activity (specifically patenting and citations data) to explore differences in the characteristics of cleantech firms such as size, turnover and amount of funding received. We also examine the time lag between patenting and venture capital funding to provide an indication of whether investment has led or followed innovation.

Finally we examine the characteristics of investors operating in the sector, firstly to understand whether an analysis of investors portfolios provides evidence of specialisation for supporting innovative (patenting) vs. non-innovative (not patenting) firms using basic statistical tests. Secondly we use a qualitative analysis of the combined investment activity of venture capitalists in cleantech to map out the investment structure and identify patterns of investment activity related to our measures of innovation.

3.1 Method

The analysis in the paper is divided into three parts; firstly we examine the patenting activity of cleantech firms using descriptive statistics and t-tests. Secondly we look at investors' behaviour according to the patenting activity in their portfolio using summary tables and t-tests, thirdly we look at the investors' behaviour from a network perspective using social network analysis tool called Pajek (De Nooy et al, 2005) to understand qualitative differences in investors' strategies. The specific approach is described in more detail in each relevant section. The combination of approaches aims to provide a useful basis to assess the development of the relationship between technological innovation and venture capital in the cleantech sector.

3.2 Data

The data used in this paper is based on the Cleantech Network database of venture funded firms in the UK. We record the total investment received by firms funded by venture capitalists between July 2001 and September 2009[2] for firms headquartered in the UK. We match these firms to the FAME database to check the firm status and obtain available data on the most recent revenue, profit and employment figures. We also collected data on whether a firm in our sample was granted a patent between 1963 and September 2009 in the UK Patent Office and recorded all characteristics (e.g. patent number, application and grant dates,

[2] The investment history for these firms is to the end of November 2009

number of citations made and received, International Patent Classes the patents are assigned to) of the patents assigned to these firms[3].

3.3 Patents as indicators of innovation

The literature raises a number of methodological concerns about using patent data as an innovation indicator. Griliches (1990) notes that not all inventions are patentable and industries differ significantly on the basis of their propensity to patent. Industries like pharmaceuticals and chemicals (i.e. science based sectors) are known to use patents most frequently while other industries have lower propensities to patent (Chabchoub and Niosi, 2005). Comanor and Scherer (1969) add that the patenting propensity does also change across firms within an industry. Moreover, it is not always clear how one can correctly assign a patent to an economically relevant industry (Griliches, 1990).

To address these concerns, we limit our interpretation of patent data to simply a ‘signal’ of innovative activity rather than a strict indicator of innovative products and processes. We distinguish between firms that have applied for a patent and those that have not. While we do not claim firms that hold patents are non-innovative; we argue that firms that with patents are in general more innovative and potentially in a better position to exploit the returns of these innovations by protecting the intellectual property rights.

The most important challenge in using patents as an innovation indicator, however, is the extremely skewed distribution of the value of patents (Silverberg and Verspagen, 2007). Patent counts are considered noisy measures of innovation as the quality of patents varies widely even within the same industry and most patents “include minor improvements of little economic value” (Griliches, 1990; p.1666). To deal with the heterogeneous quality of patents

[3] Patents are indicators of innovative activity, for which the firm wishes to exclude potential rivals from copying an innovative idea, product or process.

in our sample, we filter out the less important patents by weighting every patent by the number of citations it has received since its grant date (Jaffe, 1990). The main assumption is that more important patents get cited more frequently. Therefore, weighting patents by the number of citations received distinguishes more important patents from less important ones and reduces the noise associated with using only raw patent counts (Jaffe and Trajtenberg, 2002). Specifically, part of our analysis focuses on 39 'highly cited patents' that have received a minimum of 5 citations. These highly cited patents constitute a good representation of the most important innovations conducted within our sample while also allowing us to distinguish firms further based on the importance of their innovative activity.

3.4 Technological characteristics of the most innovative patents

We use the International Patent Classes (IPC) to explore the technological characteristics of the 39 highly cited patents in our sample. Patent examiners assign patents into patent classes maintained by World Intellectual Property Organisation (WIPO) and it is in the best interest of the examiners to classify all patents carefully as they regularly use these classifications for searching the state of the art (Lerner, 1994). IPC have been used to explore the technological fields patents belong to .

The 39 highly cited patents in the sample are assigned to 140 different IPC classes. The most concentrated IPC classes include **F03B** (003/00; 003/04; 011/00; 013/00; 013/10; 013/12; 013/26; 017/00 and 017/06)); **F01L (**001/02; 001/34 001/344 and 013/00**); H01M** (004/86; 008/02; 008/10 and 008/12).

The specific patents assigned to F03B in our sample are related to combinations and adaptations of machines and engines for special use in the context of power stations; use of tide energy (and liquid flow) as well as electric generators. The patents in the IPC class H01M relate to the manufacture of fuel cells. Finally, the patents in IPC class F01L relate to valve-gear and valve arrangements (often used in internal combustion engines).

The 'highly cited patents' get their citations from a wide range of technological areas which is evident in the 671 different IPC classes, the 406 (citing) patents are assigned to.

The most concentrated IPC classes for the citing patents are also **F03B** (013/00; 013/10; 013/26; 017/00 and 017/06); **H01M** (004/86; 008/02; 008/10 and 008/12) and **F01L** (001/04; 001/47; 001/34 and 001/344).

It appears that the main areas of technological activity among the 'highly cited patents' and the patents that cite these generally overlap, being specialized in the three IPC classes highlighted in Table 2. The increased intensity of citing patents in the field of H01M possibly relates to the rising needs for fuel cells due to applications in hydrogen, electric and hybrid vehicles.

Table 2: A comparison of the IPC classes for the 'highly cited patents' and the patents that cite these

	F03B	**H01M**	**F01L**	TOTAL
Highly Cited Patents: Share of IPC Classes	47.14%	14.29%	20.71%	82.14%
Citing Patents: Share of IPC Classes	30.95%	25.87%	20.67%	77.48%

4 Innovation characteristics of the UK clean-tech firms

Table 3 summarizes the characteristics of patenting activity among the 239 firms in our sample. Around one third of the firms have been granted at least 1 patent between 1963 and 2009 while two thirds of the firms do not own any patents. Among the 80 firms that own at least one patent, 25 firms own only one patent and 56 firms own less than six patents. 24 firms (coinciding to 10% of patentees) own more than five patents.

Table 3: Distribution of patents in the sample of UK VC funded firms

Number of Patentees	80 (33.4%)
Number of Non-Patentees	159 (66.6%)
Number of Firms with 1 patent	25 (7.6%)
Number of Firms with 2-5 patents	31 (13%)
Number of Firms with 6-10 patents	10 (4.2%)
Number of Firms with 11-25 patents	11 (4.6%)
Number of Firms with more than 25 patents	3 (1.3%)
Total Number of firms	239 (100%)

Table 4 shows a summary of firms' size (proxied by turnover and employment) and investment history (proxied by external investment received and the total rounds of investment received). We compare patentee firms with their non-patentee counterparts. T-tests confirm that the means of total investments and total rounds of investment are significantly higher for patentee firms. Interestingly, the turnover of patentee firms are significantly smaller compared to non-patentee firms, however the size of patentee firms in terms of employment data are not significantly different.. These suggest that innovative firms, despite being smaller, have been more successful in attracting VC investments.

Table 4: A comparison of Patentee and Non-Patentee firms

Non-Patentees						
	Number of Observations	***Mean***	***Std Deviation***	***Minimum***	***Maximum***	
Number of Employees	47	367.15	2048.1	1	14060	
Turnover (£000)	44	60820.92	255180.5	.24	1617300	
Investment (£000)	159	5.32	8.67	0	50	
Count of Rounds	159	1.40	.89	1	6	

Patentees						
	Number of Observations	***Mean***	***Std Deviation***	***Minimum***	***Maximum***	***Sig***
Number of Employees	21	31.24	31.13	3	124	
Turnover (£000)	28	1324.64	2685.19	13.91	12649	***
Investment (£000)	80	9.78	15.87	0	91.35	***
Count of Rounds	80	2.01	1.47	1	9	***

Note: *** 1% significance level, ** 5% significance, * 10% significance.

As previously discussed, the number of citations received by a patent signals the importance of the innovation. Hence, we expect more highly cited patents to account for more important and radical innovations (Jaffe and Trajtenberg., 2002). Moreover, evidence confirms that citation counts are found positively correlated with economic value of patents suggesting that more cited patents are more important (Hall et al., 2005).

The 80 patentee firms in our sample have a total of 471 patents and the number of citations per patent ranges between 0 and 41. The average citation per patent in the sample is 1.87. Table 5 shows the distribution of citations received for the patents in the sample. This is a clear indicator of the right skewed distribution of the value and importance of patents as almost half of the patents have not received any citations and only 8.28% of the patents have received 5 citations or more.

Table 5: Distribution of citations

	0 citation	***1 citation***	***2-4 citations***	***5-10 citations***	***11-20 citations***	***21 or more citations***
Number of Patents	228	113	91	27	9	3
%	48.41	23.99	19.32	5.73	1.91	0.64

We focus on the 39 *'highly cited patents'* that have received a minimum of 5 citations. Our investigations show that these 39 patents belong to a total of 16 companies where three firms account for the 64% of the 39 highly cited patents. Interestingly, only 4 of these 16 firms are among the top 10 firms with the highest number of patents in the whole dataset. This further confirms that the quantity of patents a firm holds is not always highly correlated with the quality of its patents.

In Table 6, we compare the characteristics of the firms that own at least one highly cited patent with the patentees that do not own any highly cited patents. As the comparisons suggest, firms that own at least one highly cited patent have larger patent portfolio compared to the rest of the patentee firms and received higher levels of investment funding over a higher number of rounds. T-tests reveal that the differences in the amount of total investment funding received by firms that own highly cited patents and the rest of the patentee firms are not significant. However, firms that own highly cited patents have received funding over more rounds, suggesting that these firms have been more successful in attracting repeat funding. Firms with highly cited patents are not statistically different in size from the rest of patentees when number of employees and turnover is used as the measure of firm size.

Table 6: A comparison of patentees based on ownership of highly cited patents

	Patentees with at least One Highly Cited Patent					
	Number of Observations	***Mean***	***Std Deviation***	***Minimum***	***Maximum***	***Sig.***
Count of Patents	16	11.69	13.37	1	57	***
Number of Employees	5	30.2	16.71	10	56	
Turnover (£000)	5	1810.21	2852.423	113	6880.333	
Investment (£000)	16	14.01875	14.3229	.59	47.03	
Count of Rounds	16	2.6875	1.537043	1	5	**

	Patentees with No Highly Cited Patents				
	Number of Observations	***Mean***	***Std Deviation***	***Minimum***	***Maximum***
Count of Patents	64	4.84	7.42	1	43
Number of Employees	15	31.56	34.89	3	124
Turnover (£000)	23	1219.09	2702.66	13.91	12649
Investment (£000)	64	8.72	16.16	0	91.35
Count of Rounds	64	1.84	1.41	1	9

Note: *** 1% significance level, ** 5% significance, * 10% significance.

4.1 Investment timing

A key question in the literature is whether investment supports very early stage innovation, or simply commercialises the innovative output of new firms. To gain an insight into the timing of innovation and investment we use patent records to establish whether venture capital leads or follows innovation. We examine the 80 firms with patents granted and measure the number of years between the first patent applications or date the first patent was granted and the first round of venture capital investment[4]. Figure 2 below shows the distribution of firms in the sample according to the timing between first successful patent application (2a) or first patent granted (2b) and the first round of venture capital. On average a firm receives the first round of investment 1.9 years after the first successful patent application or 0.5years after the

[4] We examine data for successful patent applications only

granted date, indicating on average that investment follows the receipt of a patent. However the distributions show that 16% of firms received investment in the years leading up to a patent application, suggesting some investment is used in a supporting role of finance in the innovation process. A far higher proportion of firms (48%) received investment prior to being granted a patent, however as a substantial amount of innovative effort is required to apply for a patent in the first instance, investment in the period between patent application and grant is likely follow rather than lead innovation.

Figure 2a – Distribution of firms according to the timing between patent application and first venture capital round

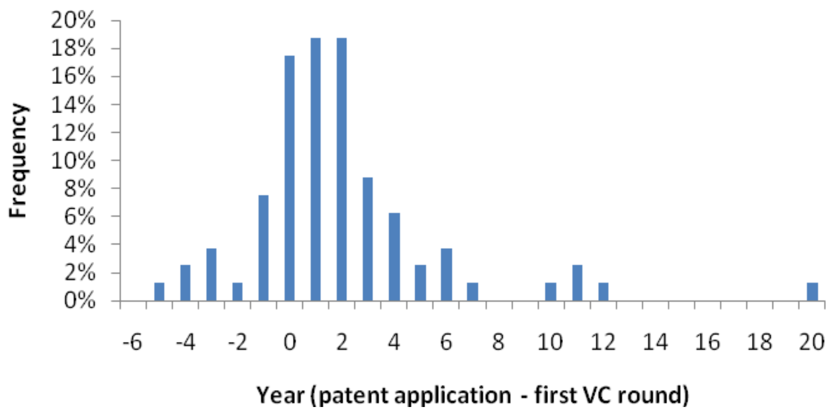
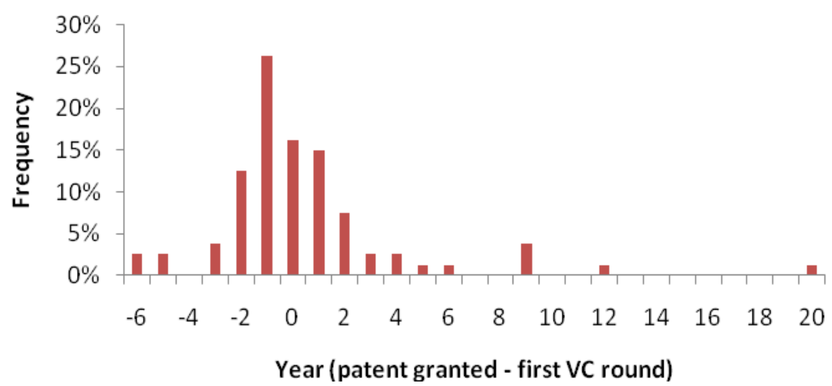


Figure 2b – Distribution of firms according to the timing between patent grant and first venture capital round



5 Investor statistics

In this section we examine the relationship between patenting activity and investor behaviour. Specifically, we look at the specialisation of investors according to whether they actively invest in patenting firms and to the assignees of highly cited patents. We seek to understand whether patenting has implications for the type of investors involved in funding.

Our analysis is based on the activity of 275 investors who provided finance to the 239 firms in our sample. The distribution of investment activity is skewed; a minority of investors are highly active, whilst the majority invest in a small number of firms. We use the investment history for each investor in the cleantech sector to capture and analyse their 'cleantech portfolio'. Specifically we measure the size of portfolio in terms of the number of firms they have invested in.

We also measure the total value of rounds each investor has been involved with, as well as the average round size per portfolio firm (PF). We estimate the approximate contribution of each investor, using information on the syndicate size to calculate each investor's overall commitment, and commitment per firm[5]. We repeat this analysis for rounds at the early stage (seed and first round deals), to provide more detail on investors' preference for risk and early stage innovation. Investment in start-ups is expected to be high risk because of the unproven nature of both the firm and any innovation being developed.

We examine the 'spread' or coverage of each investor's portfolio according to the 11 different primary industries, using the industry definitions provided by Cleantech Networks shown in Table 1. We also analyse the patenting behaviour of firms in each investor's portfolio, counting the total number of patents in the portfolio, the average number of patents per firm and the proportion of patentee firms in the portfolio. We provide similar statistics

[5] For example a round value of £10m involving a syndicate of four investors, is estimated to involve a commitment of £2.5m per investor. This is an estimate as syndicates may involve uneven contributions depending on the share of the company each investor holds

for each investor's portfolio based on citation information. Finally, using network analysis, we include a measure of each investor's centrality based on the extent to which venture capitalists' investment patterns overlap. In this analysis the most central investors share affiliations to the same portfolio firms and as a result, have extensive links with other investors. Thus centrality also measures an investor's position in the industry relative to their peers.

5.1 Investor differences based on patenting in the investment portfolio

Table 7: A comparison of investors according to the patents in their portfolio

	Investors with no patenting firms in their portfolio				
Variable	***Number of Observations***	***Mean***	***Std Deviation***	***Minimum***	***Maximum***
Count of PF	135	1.23	0.63	1.00	6.00
Total round value	135	9.93	11.60	0.00	51.70
Round value/PF	135	7.24	8.07	0.00	30.00
Approx. commitment	135	3.87	4.89	0.00	30.00
Approx. commitment/PF	135	3.24	4.42	0.00	30.00
Primary ind.	135	1.14	0.39	1.00	3.00
Centrality	135	0.01	0.02	0.00	0.07
Seed round value	135	0.25	0.84	0.00	5.94
Seed round/PF	135	0.15	0.45	0.00	2.85
First round value	135	1.85	3.79	0.00	20.90
First round/PF	135	1.47	3.39	0.00	20.90

	Investors with at least one patenting firm in their portfolio					
Variable	***Number of Observations***	***Mean***	***Std Deviation***	***Minimum***	***Maximum***	***Sig.***
Count of PF	140	2.47	2.66	1.00	20.00	***
Total round value	140	21.00	26.00	0.00	159.00	***
Round value/PF	140	6.66	6.17	0.00	26.00	
Approx. commitment	140	7.32	9.97	0.00	66.70	***
Approx. commitment/PF	140	3.45	4.31	0.00	27.60	
Primary ind.	140	1.93	1.44	1.00	8.00	***
Centrality	140	0.03	0.03	0.00	0.23	***
Seed round value	140	0.88	1.99	0.00	11.30	***
Seed round/PF	140	0.27	0.67	0.00	3.20	*
First round value	140	5.82	8.38	0.00	33.70	***
First round/PF	140	2.31	4.55	0.00	26.00	*

Note: *** 1% significance level, ** 5% significance, * 10% significance.

The results of the t-tests for Table 7 indicate that investors supporting patenting firms are more active overall, having both larger portfolios and participating in larger total financing rounds, although the average total investment activity per round and firm is not statistically different between the two groups of investors. However, at the early start-up stages (seed and first round) we find the group of investors involved with patenting firms are more active and also associated with more funding per round and per firm. Hence, in agreement with the concept of risk capital, investors supporting patenting firms are more active in the early stages of firm start-up.

Investors supporting patenting firms are also more active across a range of industries, suggesting a relatively generalist approach to investment. They occupy more central network positions than their counterpart investors who do not support patenting firms. These results indicate that investors involved with patenting firms are more closely connected to their peer group and so more closely aligned with the core Cleantech investment deals. Secondly, this analysis also suggests that the core of Cleantech activity is not specific to a particular industry or sub-industry, in agreement with the concentration ratio in Figure 2.

5.2 Investor Differences Based on Patent citations in the Investment Portfolio

In Table 8, we restrict our analysis to the activity of 140 investors who have invested in at least one patenting firm. It shows the activity of investors grouped according to whether their portfolio contains a firm with a patent citation. The majority of investors connected to patenting firms (117) have supported a firm with at least one cited patent, on average having 18.8 citations per portfolio firm. In contrast to Table 7, no statistically significant difference is found between the two groups based on the number of firms in each investor's portfolio.

Table 8: A comparison of investors according to cited patents in their portfolio

Investors with no cited patents in their portfolio

Variable	*Number of Observations*	*Mean*	*Std Deviation*	*Minimum*	*Maximum*
Count of PF	23	2.09	1.62	1.00	7.00
Count of Patenting PF	23	1.04	0.21	1.00	2.00
Count of patents	23	1.78	1.41	1.00	7.00
No. patenting PF/No. PF	23	0.70	0.32	0.14	1.00
No. of patents/PF	23	1.30	1.44	0.14	7.00
Total round value	23	7.01	8.77	0.39	31.00
Round value/PF	23	4.31	6.63	0.20	24.00
Approx. commitment	23	2.80	2.95	0.37	11.10
Approx. commitment/PF	23	1.72	1.91	0.20	6.00
Primary ind.	23	1.74	1.01	1.00	4.00
Centrality	23	0.00	0.00	0.00	0.00
Seed round value	23	0.01	0.02	0.00	0.06
Seed round/PF	23	0.94	1.65	0.00	7.58
First round value	23	0.40	0.70	0.00	3.04
First round/PF	23	3.32	6.91	0.00	24.00

Investors with at least one cited patent in their portfolio

Variable	*Number of Observations*	*Mean*	*Std Deviation*	*Minimum*	*Maximum*	*Sig.*
Count of PF	117	2.55	2.81	1.00	20.00	
Count of Patenting PF	117	1.55	1.11	1.00	8.00	***
Count of patents	117	0.80	0.27	0.20	1.00	***
No. of patents/PF	117	7.50	9.67	0.20	57.00	***
Total round value	117	18.75	43.14	0.20	214.00	***
Round value/PF	117	23.80	27.40	0.00	159.00	*
Approx. commitment	117	7.12	6.00	0.00	26.00	***
Approx. commitment/PF	117	8.20	10.60	0.00	66.70	***
Primary ind.	117	3.80	4.57	0.00	27.60	
Centrality	117	1.97	1.51	1.00	8.00	***
Seed round value	117	0.09	0.28	0.00	1.00	
Seed round/PF	117	0.03	0.03	0.00	0.23	
First round value	117	0.87	2.05	0.00	0.00	*
First round/PF	117	0.24	0.66	0.00	3.20	

Note: *** 1% significance level, ** 5% significance, * 10% significance.

Investors associated with firms owning cited patents have a higher number of patentee firms in their portfolios as well as a higher number of patents per portfolio firm. This group of investors is also involved in larger average investment round values. The statistical difference between the investor groups according to their estimated commitment also supports that the larger round value is the result of larger average investments from each investor, rather than larger number of investors working in a syndicate.

Despite finding differences between investors based on the citation patterns of portfolio firms, there is little evidence of technology specialisation. For instance, the range of industries covered by investors is similar between groups, whilst the centrality of investors connected to cited patents is higher than the group of investors that is not connected to cited patents. Note that a higher centrality figure may also indicate a generalist investment approach.

The results in Table 8 demonstrate little difference between the two investor groups according to their early stage investment activity. Whilst Table 8 shows investors supporting high quality innovation (proxied by cited patents) have a higher level of investment activity overall, this is not found at the earliest investment stages. Thus, suggesting differences in the total investment activity between groups result from late stage investment activity. One potential explanation for the late stage investment preferences of investors working with high quality firms may be investor expertise. Expertise and experience may help investors to initially select the right opportunities (i.e. high quality firms) and then provide greater amounts of funding at a later stage[6]. Alternatively, an investment strategy biased towards late stage investment is lower risk, as the innovative quality of a firm can be identified more easily.

5.3 Investor differences based on ownership of highly cited patents in the investment portfolio

Table 9 shows summary statistics for the same group of 140 investors used in Table 8, however the group is split between those investors that have/have not financed a firm with a

[6] As citations are time lagged, our measure of innovation quality is biased towards firms with older patents.

highly cited patent. Of the 140 investors supporting patenting firms, 49 have invested in a firm with a highly cited patent. The t-test results show that investors supporting firms with highly cited patents are more active, with larger portfolios in terms of the number of firms and the amount of overall investment. The portfolio of investors with highly cited patents are also more biased towards firms signalling innovation, indicating a potential strategy of focusing on more innovative firms. Yet, as with Table 7 and 8, again, we find that investors associated with the highest quality innovators (i.e. firms with highly cited patents) have interests across a wider range of industries. Additionally, despite the focus on more innovative firms, investors with highly cited patentee firms do not invest more per round or commit more investment per firm. Likewise investment at the earliest stages is also similar between groups.

The results in this section have shown specific differences between investors based on their preference for patenting firms. It has shown that investors associated with patenting firms generally have a larger portfolio and pursue opportunities across different industries. Centrality statistics suggest that investors in patenting firms are more central, or more connected, potentially as a result of their larger scale of operation. We find that whilst investing in patentee a firm is linked with investors who are more active overall, there is only weak evidence of increased investment at the round or firm level.

Table 9: A comparison of investors according to highly cited patents in their portfolio

Investors with no highly cited patent in their portfolio						
Variable	***Number of Observations***	***Mean***	***Std Deviation***	***Minimum***	***Maximum***	***Sig.***
Count of PF	91	2.05	1.96	1.00	14.00	
Count of Patenting PF	91	1.23	0.56	1.00	4.00	
Count of patents	91	8.56	12.64	1.00	55.00	
Count of citations	91	6.80	11.61	0.00	65.00	
No. patenting PF/No. PF	91	0.80	0.28	0.14	1.00	
No. of patents/PF	91	5.44	8.94	0.14	43.00	
No. of citations/PF	91	4.35	7.71	0.00	33.00	
Total round value	91	14.50	16.50	0.00	66.80	
Round value/PF	91	6.56	6.93	0.00	26.00	
Approx. commitment	91	4.81	5.22	0.00	27.60	
Approx. commitment/PF	91	3.17	4.48	0.00	27.60	
Primary ind.	91	1.70	1.30	1.00	8.00	
Centrality	91	0.02	0.02	0.00	0.16	
Seed round value	91	0.65	1.49	0.00	7.58	
Seed round/PF	91	0.29	0.73	0.00	3.20	
First round value	91	4.97	8.28	0.00	33.70	
First round/PF	91	2.63	5.38	0.00	26.00	

Investors with at least one highly cited patent in their portfolio						
Variable	***Number of Observations***	***Mean***	***Std Deviation***	***Minimum***	***Maximum***	***Sig.***
Count of PF	49	3.24	3.51	1.00	20.00	**
Count of Patenting PF	49	1.90	1.49	1.00	8.00	***
Count of patents	49	19.73	22.85	1.00	95.00	***
Count of citations	49	60.73	76.84	5.00	289.00	***
No. patenting PF/No. PF	49	0.76	0.27	0.25	1.00	***
No. of patents/PF	49	8.40	9.30	1.00	57.00	*
No. of citations/PF	49	36.70	61.90	1.00	214.00	***
Total round value	49	33.20	35.00	0.00	159.00	***
Round value/PF	49	6.84	4.47	0.00	21.40	
Approx. commitment	49	12.00	14.20	0.00	66.70	***
Approx. commitment/PF	49	3.98	3.97	0.00	20.20	
Primary ind.	49	2.35	1.60	1.00	7.00	**
Centrality	49	0.04	0.04	0.00	0.23	***
Seed round value	49	1.31	2.64	0.00	11.30	
Seed round/PF	49	0.23	0.53	0.00	3.15	
First round value	49	7.40	8.41	0.00	32.70	
First round/PF	49	1.71	2.25	0.00	12.00	

Note: *** 1% significance level, ** 5% significance, * 10% significance

Progressing from Table 7, to 8 and 9, we increase the quality of our measure of innovation that defines the two investor groups. As this quality measure is increased, it is not associated with greater investor specialisation, in terms of the industry coverage, or greater contributions to early stage investments. This result is suggestive of experimental investor behaviour, whereby the largest investors operate a broad portfolio investigating many different opportunities. The presence of a patent acts as the most important signal for investors seeking to support start-up firms. Innovation quality (as proxied by citations) appears to be harder for investors to determine, and may only become apparent in the later investment stages.

The next stage is to assess the collective properties of the investors operating in the sector. Building on the centrality statistics, we can use network representations to understand the connections between investors. We aim to explore to what extent the investor groups identified above are working together, providing investment to the same firms, and whether the measures of patenting and citation activity provide insights on the specialisation of investor activity.

6 Network analysis

Investor network diagrams (in the appendix) show links between investors who have provided funds to the same firm. It indicates whether the 274 active cleantech investors have followed related or divergent investment strategies. The size of the node (dot) indicates a weighting related to an investor's characteristics. Whilst node sizes can be compared within each diagram, it is not possible to compare node sizes across diagrams as different scaling is used. The thickness of the connecting line between nodes reflects the number of portfolio firms the two investors share. The thicker the line, the more times both investors have provided funds to the same firm, and therefore, the more similar their investment strategy.

6.1 General outline of the cleantech network

Figure 3a shows the basic network relationship resulting from overlapping investor portfolios. The more central an investor's position in the network, the greater their ties to their peer group. In Figure 3a, the network appears to have a definite core structure in which high centralities reflect that investors' investment patterns are related to the core of activity in the sector. The thicker connecting lines towards the centre suggest that some central investors have repeatedly funded the same set of firms, often working together and having similar investment strategies related to specific firms.

Figure 3a also shows a peripheral set of unconnected investors following divergent investment strategies: typically these divergent investors are operating on the margins of the sector, with exposure to a minority of deals. When each investor node is coded according to whether they have at least one patenting firm in their portfolio (yellow = patenting; blue = non-patenting), we find that investors with patenting firms are more central, a result also suggested in Table 7.

Figure 3b, shows the same network overlaid with node weights related to the number of patents held in each investor's portfolio. As expected, the more active the investor, the more likely they will accumulate patenting firms and the more central their position will be in the network. However, some peripheral investors also are associated with patenting firms, indicating more selective strategies in the peripheral groups.

In figure 4 we change the node weights to show the total value of rounds each investor is associated with (4a), and the average value of each investor's round (4b). Figure 4a shows the greater financial contribution of central investors active in patenting firms compared to the smaller contribution of investors in more peripheral positions. Figure 4b, on the other hand, highlights more divergent strategies of investors according to their location in the network. Peripheral investors are shown to be more committed to specific opportunities than investors located in the centre, often providing significant rounds of finance to firms without a patent. In contrast investors with a strong cleantech sector presence (i.e. big investors in the sector) often support patenting firms, but provide smaller rounds of finance, suggesting an experimental strategy, providing smaller investment rounds to many different firms.

6.2 Early stage funding in the cleantech network

In Figure 5 the network nodes are scaled by each investor's seed funding activity. Only a minority of investors are active at the seed funding stage, but Figure 5 shows a similar pattern to Figure 4. The most central investors provide a significant financial contribution at the industry level, but relatively small amounts of finance per round compared to their more peripheral counterparts. The results of Table 7 indicate that investors with patentee firms in their portfolio are associated with higher levels of investment overall and per round. However, Figure 5 contributes greater detail to the analysis, demonstrating the relative importance of different investors to the overall industry investment pattern compared to average round sizes. Those investors most active overall are significant contributors to early stage investment, but the largest contributions to patentee firms are from investors located towards the periphery of the network. This observation may indicate divergent strategies of investors supporting patenting firms, whereby the more active investors prefer to manage the risk of supporting innovative early stage firms by providing small tranches of finance to test their ideas for commercial application, and so opt for a diversification strategy. Investors with a smaller exposure to cleantech overall, but have invested in patentee firms providing larger rounds to a smaller number of early stage firms.

In Figure 6 the network nodes are scaled by each investor's total first round investment (6a), and average first round value (6b). In both Figure 6a and 6b we find a strong presence of investors with patentee firms (i.e. yellow nodes are more prominent/larger). However, in Figure 6a the investors with the largest nodes appear away from the centre, in contrast to 4a and 5a, and also appear grouped together. This smaller cluster of investors is highly active at the first round stage generally, but also involved in providing larger rounds focused to specific firms. The position of the cluster away from the centre also suggests a focused investment strategy. The presence of a cluster suggests a specialised group of investors who are active in the early investment stages but also provide strong support to individual firms.

6.3 Funding of the highly cited patentee firms in the cleantech network

In Figure 7 the nodes are re-coded to show whether investors' portfolio contain a highly cited patent (yellow = highly cited patent). The general pattern described in Figure 3a is repeated; however the position of investors supporting firms with highly cited patents is less concentrated to the centre of the network. Comparing Figure 7 (a and b) with Figures 5b and 6b also supports our earlier argument that investors with an interest in early stage investment are less responsive to the innovation quality as proxied by citations. For instance, comparing Figures 6 and 7 shows the small groupings of active first round investors identified in Figure 6 are not involved with cited patents in Figure 7.

Finally Figure 8a shows the industry coverage of each investor and reflects our earlier assumption that the most central investors have activity distributed across several industries. In contrast, more peripheral investors are active in fewer industries.

7 Discussion

Our results provide evidence for significant variation in the patenting behaviour of cleantech firms and the strategy of the investors. In the 239 firms analysed, we find the majority are not patenting firms, yet are funded by venture capitalists. Facing urgent environmental challenges, one would expect this sector to be concerned with finding solutions to replace fossil fuel based technology with more renewable and environmentally friendly technology. Yet many firms in our sample have yet to patent and may related to the relatively young and small size of firms in our sample- where innovation is at an early stage. However, the fact that a significant amount of investment beyond the seed phase has been allocated to many of these firms suggests that technological development is not necessarily a critical part of firm strategy for many of the firms analysed. This raises questions about the types of firms and technologies the venture capitalists prefer to fund in the cleantech sector and whether this is well aligned with the government agenda on moving towards a low carbon economy.

Even firms with patents often have a small patent portfolio; over half of the patenting firms have less than 5 patents. Patenting firms are rewarded with greater levels of investment, despite having a lower turnover than their non-patenting counterparts, suggesting that patenting firms require more investment to support them through their development phase, prior to achieving significant inflows of turnover. This observation fits well with the classic role of the venture capitalist as the ‘technology gatekeeper’.

Likewise, our analysis of investor behaviour shows differences between investors with patenting firms in their portfolio versus those without. Specifically, investors who have funded at least one patenting firm tend to be larger, provide more investment to the sector overall and are active across several industries. In this case, in agreement with Niosi (2003) patents seem to act as a signal for investment. The patent signal attracts larger investors who have greater levels of investment activity at the early stages as well as contributing more in each early stage round on average.

However, the network analysis reveals the heterogeneity within these groupings of investors based on patenting vs. non-patenting property of their portfolios. The key investors that invest large amounts at the sector level do so by funding many different firms, rather than providing large amounts of funding to particular firms. Moreover, the network analysis shows that those investors supporting particular patentee firms at the early stages are formed of smaller groups of more specialised, less central, less extensively linked investors, who fund less firms, but are more supportive of those firms. The network analysis highlights that larger investors take a more generalist approach funding patenting and non-patenting firms and investing in many different areas. Such a diversified or ‘spread-betting’ approach is in stark contrast to the smaller more specialised and targeted investors who contribute to larger rounds in fewer firms.

As many firms do not have cited patents our measure of the innovation quality, patent citations, is concentrated towards a small group of firms. However, firms with more cited patents (and hence higher quality innovations) are not rewarded with significantly higher levels of investment. In fact, their investment is spread over a greater number of rounds. The use of investment rounds or staging is one method of reducing risk for the investor, as they have greater control over the flow of investment into the firm. This result suggests that higher quality and more radical innovations may be perceived as higher risk by investors and result in higher levels of scrutiny for the firm

We generally find evidence that patents, rather than the quality of these patents (proxied by patent citations), are the main signal for investors, especially those most central to the industry. One explanation for these results is the unpredictable nature of innovation and the lack of information available to investors on the quality of innovation at the time of investment. For instance, at the early stages, a patent may be the most reliable signal of innovation quality, as the innovation will not be widely cited or recognized in the market, even if superior. For later stage investors, some further information on quality may come to light – which we proxy by citation information- may be useful in the in the investment decisions as reflected in the results in Table 7. The fact that we find firms with highly cited patents are not necessarily rewarded more than their non-citing competitors, but receive more oversight, suggests that whilst investors perceive the risk, the uncertain process of innovation makes it difficult to identify high quality innovators at the time of investment.

8 Conclusion

This paper has presented an initial exploration of the relationship between cleantech innovation and venture capital activity. The absence of other studies in this area, and the relatively new resurgence of investment activity in this loosely defined technology area mean we have used a simple descriptive analytical approach. The paper has indicated that the underlying technology of the cleantech sector is fragmented, and is investor led, via a core group of investors with overlapping affiliations to firms. This is perhaps not surprising as the sector has grown in parallel to increasing political pressure to reduce CO2 emission and in response to rising energy costs, as opposed to biotechnology or the Internet sectors which grew from technological breakthroughs. However, although the cleantech 'sector' may have important implications for the future development of new environmental technologies our analysis has highlighted a general absence of extensive patenting within the 239 firms sampled. The analysis has shown that patents are a valid signal for investors; however it has also shown a heterogeneous population of investors, the most active of which are involved in a general sector level- late stage approach, leaving smaller investors to support the early stages of firm development.

For the technological evolution of the sector, early stage investment and the identification of high quality innovators will be crucial. Our results suggest that investors are not supporting high quality innovators at the earliest stages, potentially because the investors are still experimenting with their investment models and the appropriate technology may still be in the most uncertain or early stages of development.

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10 Appendices

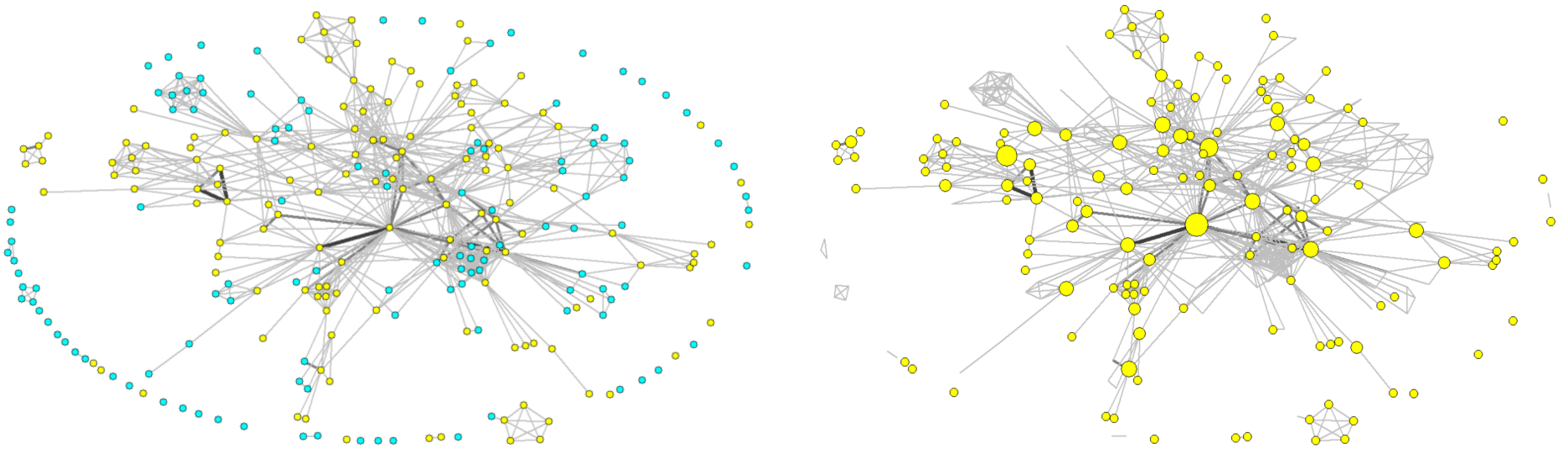
10.1 Cleantech Network industry definitions:

Extract from Cleantech Network website,“Cleantech spans many industry verticals and is defined by the following eleven segments:”

Primary Industry	Secondary Industry
Energy Generation	Wind Solar Hydro/Marine Biofuels Geothermal Other
Energy Generation	Wind Solar Hydro/Marine Biofuels Geothermal Other
Energy Storage	Fuel Cells Advanced Batteries Hybrid Systems
Energy Infrastructure	Management Transmission
Energy Efficiency	Lighting Buildings Glass Other
Transportation	Vehicles Logistics Structures Fuels
Water & Wastewater	Water Treatment Water Conservation Wastewater Treatment
Air & Environment	Cleanup/Safety Emissions Control Monitoring/Compliance Trading & Offsets
Materials	Nano Bio Chemical Other
Manufacturing/Industrial	Advanced Packaging Monitoring & Control Smart Production
Agriculture	Natural Pesticides Land Management Aquaculture
Recycling & Waste	Recycling Waste Treatment

Source: Cleantech Networks

10.2 Network representations (over the page)



Figures 3a: Investor network coded for patent/non-patent investors (above left) and 3b scaled for the number of patents held within firms in investor's portfolios (above right)

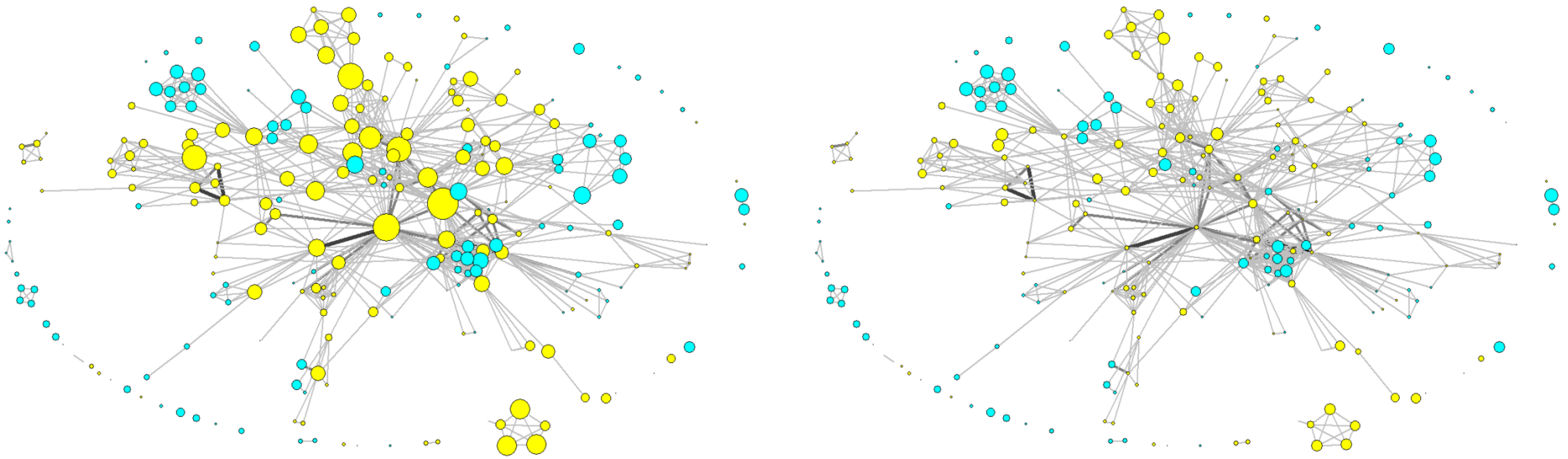


Figure 4a: Investor network coded for patent/non-patent investors, vertices scaled by total round value (above left) and 4b average round value (above right) for each investor

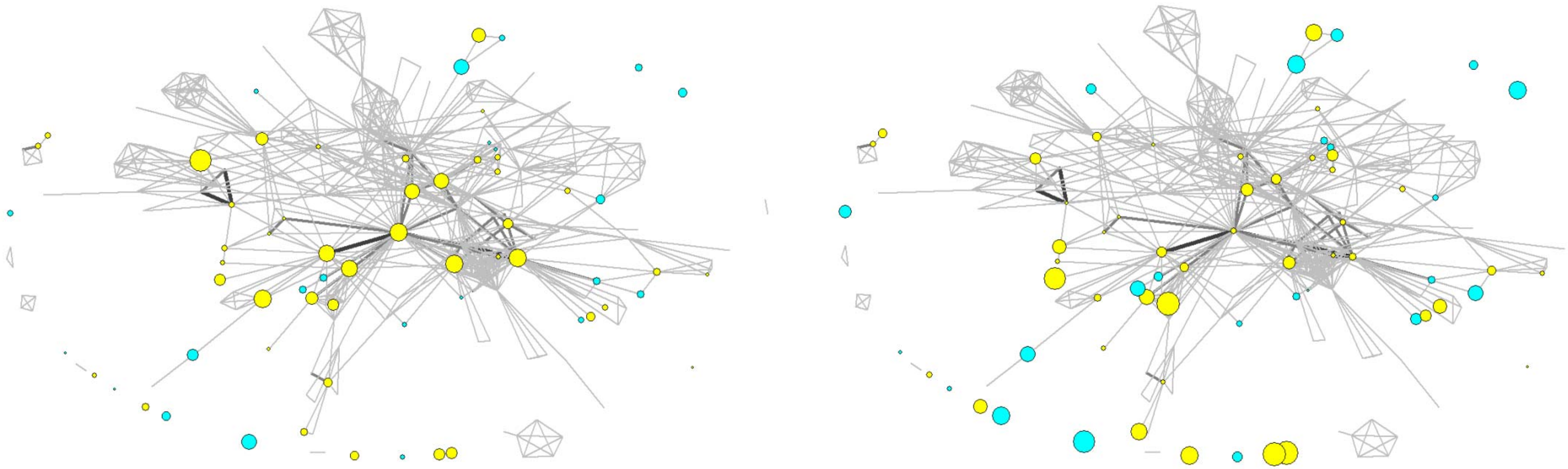


Figure 5a: Investor network coded for patent/non-patent investors, vertices scaled by seed round value (above left) and 5b average seed round (above right) for each investor

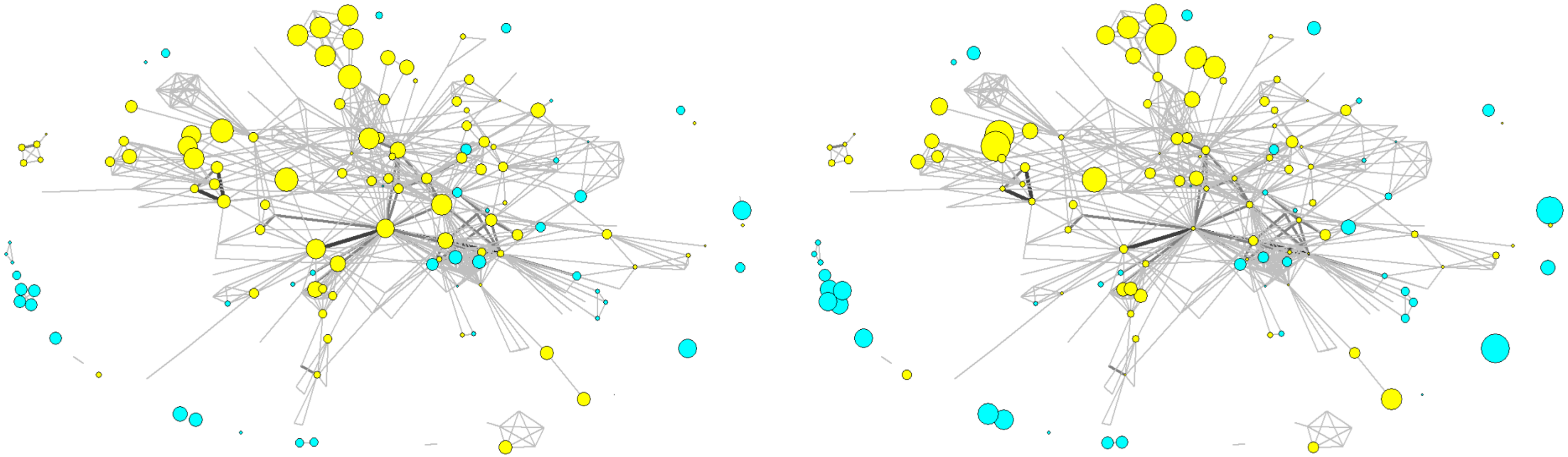


Figure 6a: Investor network coded for patent/non-patent investors, vertices scaled by first round value (above left) and 6b average first round (above right) for each investor

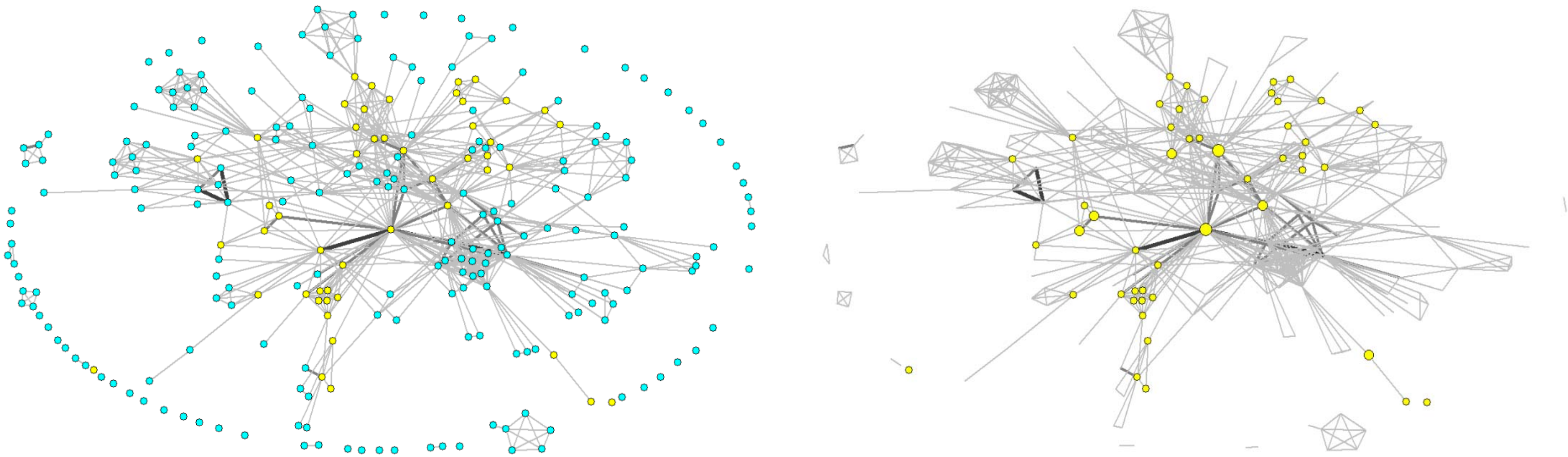


Figure 7a: Investor network coded for highly cited-patents (yellow – above left) and 7b scaled by number of highly cited patents in investor's portfolio (above right)

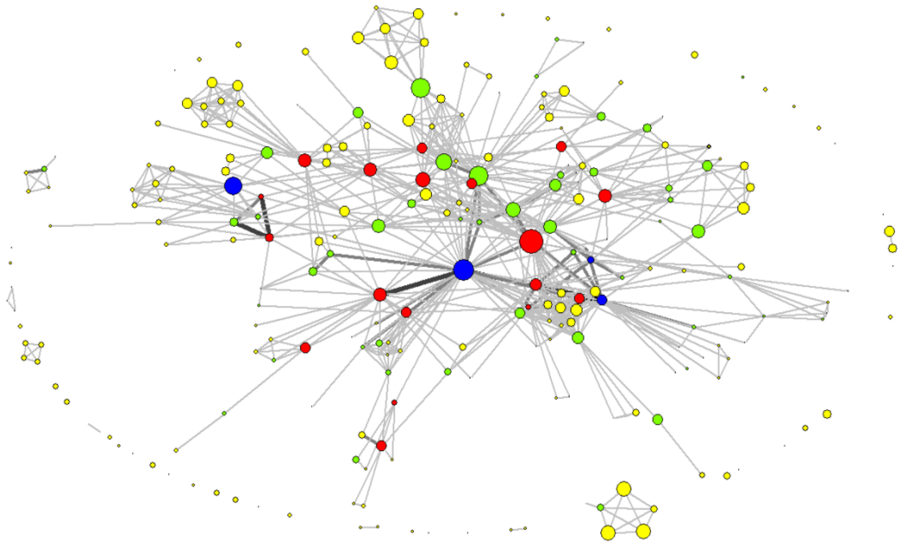


Figure 8a: Investor network coded for investors primary industry coverage (vertices coded for number of primary industries: yellow = 1-2; green = 3-4; red = 5-6; blue = 7-8)