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BARRIERS TO LOW-CARBON INNOVATION, CONSEQUENCES FOR FINANCE AND POLICY RESPONSES

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Barriers to low-carbon innovation, consequences for finance and policy responses

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Abstract: This paper analyses the field of innovation studies regarding barriers to low-carbon innovation and consequences for finance. It attempts to integrate previously separated literatures, bridge the gap between abstract failures and tangible barriers and add a temporal perspective to allow for more differentiated policy responses. Among the most salient problems for the commercialisation and diffusion of clean technologies, scholars have highlighted the financing environment. A complex set of barriers therefore revolves around the question of how to finance companies, projects and infrastructure based on low-carbon innovation. The paper contributes to a holistic understanding of the underlying mechanisms. A combination of technological barriers combined with economic barriers, institutional and political barriers contribute to thin financial market for low-carbon innovation all along the innovation cycle. Policy makers can chose from a variety of measures address these barriers and mobilise private finance. Avenues for future research relating to financing low-carbon innovation and corresponding policies are depicted.

JEL codes: O33, O38, G21, G23, G28

Keywords: Barriers to innovation; low-carbon innovation; private financing instruments; market failures; government policy

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Introduction

Global climate change has been recognised amongst the biggest 'grand challenges' facing humanity in the 21st century. There is widespread consensus among policy makers, businesses, the scientific community and wider society that the transition towards a low-carbon economy (i.e. 'green economy') is the desirable goal, which makes a sustainable life possible for all human beings by decoupling economic activity from the use of finite resources (IPCC 2014; Rosen & Guenther 2014; Marcucci & Turton 2015; IEA 2013; OECD 2009).

A critical element to achieve 'green growth' is the development and diffusion of clean technologies (eco-innovation) (Foxon et al. 2008; Mowery et al. 2010; Hargadon 2010; IPCC 2014). This process is hampered by a number of factors, relating both to the inherent characteristics of innovation and technological change, and environmental externalities (Jaffe et al. 2005; Foxon & Pearson 2008). Scholars investigated policy instruments to address these failures on an abstract level, as well as with relation to concrete technologies and contexts, to derive policy implications (Brown 2001; Gallagher et al. 2006; Leete et al. 2013; Leitner et al. 2010; Mowery et al. 2010; Hoppmann 2015).

Among the most salient barriers to the commercialisation and diffusion of clean technologies, scholars have highlighted the financing environment (Demirel & Parris 2015; Iyer et al. 2015; Jacobsson & Karltorp 2013; Leete et al. 2013; Polzin et al. 2016; Zhang et al. 2012). On the one hand, investments into R&D, commercialisation and diffusion of clean technologies remain below the socially desirable level and recent investment trends show decreasing amounts of finance dedicated to clean technologies and correspondingly, an increasing risk aversion of financiers (BNEF 2013; Chassot et al. 2014; Lüthi & Wüstenhagen 2012; Mowery et al. 2010; Mathews et al. 2010; Hargadon 2010). On the other, clean technologies require huge amounts of investments in companies, projects and infrastructure which far surpasses government funding possibilities to make new technologies competitive with incumbent technologies (Perez 2013; Mathews et al. 2010; Foxon & Pearson 2008; Huberty & Zysman 2010). Yet there is a surprisingly little amount of research in this area beyond the classical innovation finance stream of venture capital (VC) (Bocken 2015; Kenney & Hargadon 2012; Marcus et al. 2013; Olmos et al. 2012). This article therefore focuses on, and contributes to, a more holistic understanding of the peculiarities that eco-innovations face with regard to finance by answering these research questions:

1. *What are consequences of barriers to low carbon innovation for private finance?*
2. *What possibilities do policy makers have to address these barriers and mobilise private finance?*

The remainder of this paper is structured as follows: Section 2 describes the methodology used to assemble the literature base, which is then reviewed in the following chapters. Section 3 draws on a process framework for eco-innovation and organises barriers for eco-innovation accordingly, focusing on consequences for finance and addresses possible policy responses. Finally, section 4 discusses implications for policy and (future) research.

Methodology: Assembling the literature base

This paper identifies a representative base of articles that describe the barriers to low-carbon innovation, consequences for finance and possible policy solutions. Low-carbon innovation[1] can be defined as the 'invention, commercialisation and diffusion of technologies that reduce carbon emissions and/or other environmentally negative impacts and thus contributes to sustainability' (Horbach et al. 2012; Foxon & Pearson 2008; Rennings 2000). In order to finance innovation based on low-carbon technologies (companies, projects and infrastructure), a variety of private finance instruments exist (Auerswald & Branscomb 2003; Bocken 2015; Bürer & Wüstenhagen 2009; Bürer & Wüstenhagen 2009; Polzin et al. 2015). Relatedly I define a 'barrier' as a blocking mechanism, obstacle or hampering mechanism, that prevents clean technologies from being commercialised and diffused which in turn inhibits the financing environment (Bürer & Wüstenhagen 2009; Demirel & Parris 2015; Foxon & Pearson 2008; Jacobsson & Karltorp 2013; Leete et al. 2013; Polzin et al. 2016).

The methodological approach to assemble the literature has deliberately been kept simple, in order to portray a relatively broad topic and do justice to the expected heterogeneity in the literature. Essentially the goal was to identify a representative base of articles that describe the barriers to low-carbon innovation which have consequences for finance and possible policy solutions. It is neither intended to be comprehensive, nor does it ignore critical theoretical perspectives. The articles were identified and classified, the texts analysed and finally mapped into a theoretical framework (Hart 1998). Eco-innovation has been researched from a variety of perspectives including innovation systems (IS) (Jacobsson & Bergek 2011), transition studies (Markard et al. 2012), environmental and ecological economics (Fischer & Newell 2008; Böhringer et al. 2009; Newell et al. 2006), as well as energy economics and policy (Popp 2010; Jakeman et al. 2004). To gain a holistic picture of the technological, economic and institutional processes surrounding eco-innovation, an interdisciplinary approach is adopted thereby

[1] Throughout the course of the analysis eco-innovation, low-carbon innovation, innovation in clean technologies and environmental innovation will be used interchangeably.

enabling the integration of literature and debate streams, which have previously been separated.

The literature search applied certain criteria. The first choice was to include only published seminal books, established and well-regarded working paper series (i.e. NBER, CEPR) and peer-reviewed articles. Doing so assured the compiled research achieved a certain level of quality. According to Hunter & Schmidt (2004) this does not lead to an 'availability bias' for empirical studies because if the number of articles is sufficiently large, the direction of the results published and those not published tend to be the same. The second choice was to use five scientific search engines that are widely used in the community of business scholars to carry out keyword searches. The search engines reviewed include Business Source Complete, Science Direct, EBSCO, Emerald and Google Scholar.

After identifying the main articles dealing with the barriers and systemic/market imperfections related to eco-innovation, the articles have been analysed in a narrative review, revealing barriers, policy responses and consequences for finance. The analysis followed these steps:

1. Categories of barriers and policy responses were developed from the system failures literature on IS in the context of sustainability (Weber & Rohracher 2012; Edquist 2011; Klein Woolthuis et al. 2005; Eleftheriadis & Anagnostopoulou 2015; Negro et al. 2012).
2. Consequences for finance of these barriers have been highlighted (e.g. Bürer & Wüstenhagen 2009; Wüstenhagen & Menichetti 2012; Polzin et al. 2016; Demirel & Parris 2015; Bocken 2015; Kenney & Hargadon 2012).

A database containing authors, title, publication, main argument, chain of arguments, empirical or conceptual setting as well as keywords was developed. According to the main argument and keywords section, the articles have been classified for better organisation (Hart 1998). An overview about topics and the journal base can be drawn from Table 1.

Table 1: Descriptives of literature base

Journal	Topic	# papers
Business Strategy and the Environment	Venture capital, niche-regime-dynamics	2
California Management Review	Cleantech innovation, policy	2
Ecological Economics	Technical change and regulation	7
Energy Economics	Energy innovation	10

Energy policy	Specific clean technologies, renewables, policies, investments, barriers	55
Environmental Innovation and Societal Transitions	Transition studies, innovation systems, eco-innovation	3
Environmental and Resource Economics	Technological change and regulation	4
Industrial and Corporate Change	Industry dynamics and finance	3
Industry and Innovation	Innovation systems, regulation, eco-innovation	5
Journal of Cleaner Production	Low-carbon innovation, barriers, policies, innovation and diffusion	10
Journal of Business Venturing	Entrepreneurial finance	3
Renewable and Sustainable Energy Reviews	Acceptance of technologies, barriers to renewable energy technologies, policies	7
Research policy	Innovation studies, barriers, concepts	20
Technological Forecasting and Social Change	Technological innovation systems; policies and innovation, modelling	10
Technovation	System failures, innovation system for cleantech	2
Venture Capital	Entrepreneurial finance	5
Journal of Technology Transfer, American Economic Review, Entrepreneurship, Theory and Practice, Energy Research & Social Science, Technology Analysis & Strategic Management, Journal of Public Economics, Organization & Environment, Nature Climate Change, Journal of Environmental Economics and Management, Innovation and Development, Journal of Economic Behavior & Organization, Business & Society, Resource and Energy Economics, The Journal of Business, Management Research Review, Administrative Science Quarterly,	Transitions, externalities, technology diffusion, entrepreneurial finance (especially venture capital and crowdfunding), public-private partnerships, management of renewables, energy efficiency, social movements, technological change and regulation, finance innovation and growth, policies, investment risks, innovation systems for sustainability	18

Findings: Barriers to low-carbon innovation, consequences for finance and policy responses

The Innovation-finance-policy chain can be divided into three distinct phases: Technology generation including basic and applied research and development (R&D); technology commercialisation including demonstration and pre-commercial phases, and technology diffusion including niche-market/supported commercial and fully commercial. The stylised innovation-finance-chain of clean technologies represent complex interdependent phenomena which involve public actors and private financiers (Figure 1 and Figure 2) (Auerswald & Branscomb 2003; Bocken 2015; Wüstenhagen & Menichetti 2012). It offers a menu of policy responses to achieve the 'grand challenge' of low-carbon innovation and transition (Huberty & Zysman 2010).

During the basic and applied R&D stages technologies are being developed by both public (research institutes, universities) and private organisations (firms) which supply the necessary financial resources in the form of public or private research grants and subsidies. In the demonstration and early commercialisation phase business angels, family offices and VC as private financiers invest into start-ups and small innovative firms, whereas large or mature firms start to deploy internal funds for ongoing R&D and commercialisation activities. Technology is usually sufficiently mature to allow for scale up towards production which is financed by VC (Kenney & Hargadon 2012; Marcus et al. 2013) or family offices with a long-term investment strategy (Bocken 2015). Founders also draw from informal sources of capital such as family, friends and fools (Bocken 2015; Bürer & Wüstenhagen 2009). Recently crowdfunding has stepped in for the seed finance (Harrison 2013; Lehner 2013; Vasileiadou et al. 2015). Beginning with the niche-market stage, ideally the private sector actors take the lead to foster diffusion of the technology. Firms concentrate on market development. Banks, private equity investors and internal funds provide the necessary resources to finance production and marketing (Bocken 2015; Hall & Lerner 2010). Additionally institutional investors finance projects and infrastructure (Polzin et al. 2015; Wüstenhagen & Menichetti 2012).

Technological barriers – Active technology policy

The overarching technological barrier facing innovative clean technologies is technological lock-in and path dependency which relates to insufficient technological maturity or missing standards (Iyer et al. 2015; Bergek & Onufrey 2014; Foxon & Pearson 2008; del Río & Unruh 2007). This technological lock-in is translated into expectations of severe market failures and commercial viability is questioned. These developments are persistent due to suboptimal investments by private firms in clean

R&D which leads to path dependency (Hall & Lerner 2010; Hoppmann et al. 2013; Demirel & Parris 2015).

In order to address these barriers scholars suggest a long-term technology strategy (Blanford 2009). This refers to effective coordination with demand-side policies, support for transformational change across the research development and demonstration (RD&D) spectrum of activities (Hargadon 2010). Policy makers should aim at increasing technological diversity (van den Bergh 2013; Mowery et al. 2010; Jefferson 2008). This can be done by integrating environmental policy targets in technology policy and operationalising them into research programs (Kivimaa & Mickwitz 2006). These measures would allow early stage early stage financial instruments such as private R&D grants, crowdfunding to be used more effectively on those technologies that fall within this spectrum reflecting a market-based approach to sustainable innovation which many private investors (especially, VCs, private equity, business angels and banks) favour (Bocken 2015; Petty & Gruber 2011; Bruton et al. 2015; Szerb et al. 2007). Furthermore, research has shown that strategic research partnerships (public–private RD&D partnerships) among various combinations of industry, academia, national laboratories, other governmental and non-governmental entities such as SBIR, ATP or ARPA-E[2] are vehicles to overcome cooperation barriers and competence lock-ins (Chadha 2011; Sovacool 2008; Sartorius 2008; Brown 2001). Integrating private financiers has proven to be accelerating commercialisation (Lerner 1999; Link & Scott 2010).

Beginning with the demonstration phase, stakeholders start to perceive technological risks and complexity associated with these new clean technologies such as long-term performance and effects on the socio-economic and natural environment (Böhringer et al. 2009; Iyer et al. 2015; Masini & Menichetti 2012; Schleich 2009). Similarly reverse salients i.e. unanticipated political, economic and social consequences could hinder further development and commercialisation of a particular technology (Gee & McMeekin 2011). More concretely, missing stakeholder involvement proves to be a significant barrier since clean technologies usually affect a range of stakeholders throughout development, demonstration and especially diffusion phases e.g. for renewables or smart grids (Zhang et al. 2012; Hall & Kerr 2003; Enzensberger et al. 2002). As informed financiers such as business angels and family offices take these developments under consideration in their risk/return calculations, they refrain from financing companies that are active in the respective sectors (Bocken 2015; Da Rin et al. 2006).

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[2] These refer to technology programs in the US: Small Business Innovation Research (SBIR); Advanced Technology Program (ATP); Advanced Research Projects Agency – Energy (ARPA-E);

During these critical phases ('valley of death'), demonstration projects and trials as well as technology transfer programs are strongly suggested to assess and validate feasibility, commercial viability and to rule out emerging reverse salients (Hendry et al. 2010; Brown & Hendry 2009; Sartorius 2008; Lewis & Wiser 2007). Providing these results to business angels, VCs, family offices and the wider public (for crowdfunding) would reduce information asymmetries and thus facilitate investments (Bürer & Wüstenhagen 2009; Harrison 2013; Kenney & Hargadon 2012; Vasileiadou et al. 2015). Crowdfunding also distributes the risk and tackle occurring performance problems and reverse salients on a smaller scale (Belleflamme et al. 2014; Bruton et al. 2015).

Institutional barriers – Institutional creation and change

Institutional barriers comprise an institutional lock-in associated with changing patterns of behaviour, social rules and norms that favour fossil-fuel-based technologies which have been deployed throughout the last decades (Chadha 2011; Foxon & Pearson 2008; Hekkert & Negro 2009; Klein Woolthuis et al. 2005; Rennings 2000). In addition information asymmetries (incomplete or imperfect information) translate into bounded rationality that prevents clean technologies from being developed and deployed which especially affects the relationship between the financier and the innovator (Jaffe et al. 2005; Jaffe & Stavins 1994; Sanstad & Howarth 1994; Schleich 2009). Environmental economists widely suggest a combination of regulation and R&D support (van den Bergh 2013; Leitner et al. 2010; Popp 2010; Fischer & Newell 2008). However, to escape institutional lock-ins and related failures, Rennings (2000) highlights the importance of systemic approaches to consider the variety of factors surrounding complex failures.

During the demonstration stage, infrastructure problems, including physical infrastructure such as power and transport and scientific infrastructure such as high-quality universities, research laboratories and technical institutes represent a significant barrier. This relates to a more general lack of skilled staff and capabilities (Negro et al. 2012; Jacobsson & Karltorp 2013). Eco-innovation as systemic innovations depend on complementary, capital intensive assets for their commercialisation e.g. in the case of fuel cell mobility (Steinbach 2013; Zhang et al. 2012; Foxon & Pearson 2008; Köhler et al. 2010; del Río & Unruh 2007; Negro et al. 2012; Farla et al. 2010). Infrastructure poses significant financing problem as the question of ownership is oftentimes not resolved which makes it difficult for project and asset financiers to evaluate commercial viability. These private finance mechanisms rely on a long-term horizon with stable returns (Henriot 2013; Köhler et al. 2010). Therefore, policy makers should provide support for development of (grid-) infrastructure technologies and other complementary assets (Henriot 2013; Jacobsson & Karltorp 2013; Köhler et al. 2010).

When moving towards commercialisation, regulatory risk and uncertainty such as unanticipated or recurring policy changes, legal security and duration of administrative processes proves significantly hindering as low-carbon innovation exhibit a high regulatory dependency (Bergek et al. 2013; Wüstenhagen & Menichetti 2012; Haley & Schuler 2011; Böhringer et al. 2009; Blyth et al. 2007; Foxon et al. 2005; Lüthi & Wüstenhagen 2012; Lüthi & Prässler 2011; del Río & Unruh 2007). These risks represent probably the most direct risk for an investment, as many technologies and their applications along the innovation cycle directly or indirectly depend on a favourable political environment (Wiser & Pickle 1998). This affects all financial instruments although more industry specialised investors such as business angels, VC and family offices might fully understand the regulatory background and can thus evaluate corresponding risks. However banks for example refrain from lending those business as regulations are easily revocable (Bürer & Wüstenhagen 2009; Lüthi & Prässler 2011; Lüthi & Wüstenhagen 2012). As a response policy makers need to develop a certain set of skills that are detailed under section 3.5.

Beginning with pre-commercial phase and deployment, local and environmental acceptance that includes technological, economic, administrative approval and spatial planning (Dinica 2008; Iyer et al. 2015; Sovacool 2009; Steinbach 2013), negative attitudes and social values or pressure from communities hinder the spreading of innovative clean technologies (van den Bergh 2013; Smink et al. 2015; Montalvo 2008). As financiers observe the societal implications when investing into new fields, missing social acceptance poses a severe reputational risk, especially relevant for banks (Arabatzis & Myronidis 2011; Tampakis et al. 2013; Wüstenhagen et al. 2007; del Río & Unruh 2007). More informed financiers can evaluate the risks, however these financial instruments exhibit limits with regard to the volume they can finance (Jefferson 2008).

To gain broader momentum for technology development and diffusion, policy makers should work with members of different technology-specific advocacy coalitions, both private capital and various interest organisations, and involve social movements as well as stakeholders, especially for systemic innovations that require public acceptance (Hall & Kerr 2003; Jacobsson & Bergek 2004; Jacobsson & Lauber 2006; Sine & Lee 2009). This open approach involving both professional investors/lenders as well as the general public (regarding crowdfunding) could help to better understand associated risks and achieve comprises regarding their management (Bruton et al. 2015; Polzin et al. 2016).

Own representation. Framework adapted from Auerswald & Branscomb (2003); Bürer & Wüstenhagen (2009); Wüstenhagen & Menichetti (2012); Bocken (2015)

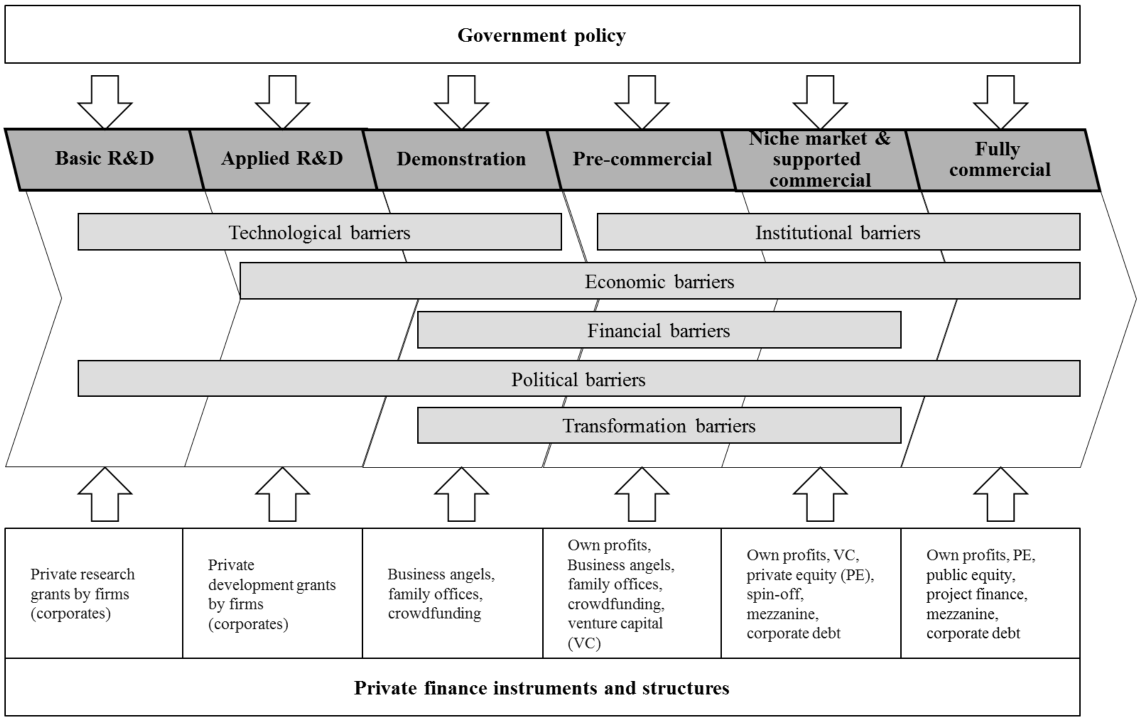

Figure 1: Barriers at the interplay between private finance instruments and government policies

Economic barriers – Fixing market failures and market creation

Economic barriers represent significant obstacles to low-carbon innovation since these technologies are subject to limited appropriability economic lock-in and corresponding path dependency due to a history of investments in fossil-fuel based technologies (Wüstenhagen & Menichetti 2012; Foxon & Pearson 2008; Rennings 2000; Negro et al. 2012). Innovative clean technologies are subject to externalities since the prices for fossil-fuel-based technologies do not incorporate their negative environmental effects (Jaffe et al. 2005; Jaffe & Stavins 1994). To address these barriers in an effective STI policy technology, push mechanisms (R&D policies) complement demand pull deployment policies (Veugelers 2012) or a more general internalization of externalities through greenhouse gas emission trading (Rogge et al. 2011; Fischer & Newell 2008; Popp et al. 2011).

In the basic and applied R&D phases (technology generation), limited appropriability and other externalities translate a general product and market uncertainty (Bosetti & Tavoni 2009; Barreto & Kemp 2008; Montalvo 2008) which results into private underinvestment in R&D (Mowery et al. 2010; Baker et al. 2009; Sovacool 2008; Nemet & Kammen

2007). To address under-investment in R&D in the early stages, R&D subsidies and grants or R&D tax credits have been suggested to alleviate financial constraints (Acemoglu et al. 2012; Popp 2010; Schilling & Esmundo 2009; Jaffe et al. 2005; Olmos et al. 2012; Loiter & Norberg-Bohm 1999; Freeman 1996). However low-carbon innovation programs need to be shaped and evaluated as portfolios that distribute their investments across degrees of risk and time frames for anticipated returns (Jaffe et al. 2005). A complementary reduction of R&D subsidies for fossil-fuel-based technologies is also strongly suggested (Schilling & Esmundo 2009; Jefferson 2008; Sovacool 2008) to show a strong signal to the financial market actors that a transition towards supporting sustainable innovations is envisioned (Polzin et al. 2016).

From demonstration to supported commercial stages, scholars refer costs for deployment, high discount rates on future savings and a corresponding 'waiting' for improvements as main barriers to commercialisation (Jaffe & Stavins 1994; Schleich 2009; van Soest & Bulte 2001; Bergek et al. 2013; Kimura 2010; Kobos et al. 2006). A lack of business models for radically new clean technologies such as the quality and price of maintenance services proves to be equally challenging (Kley et al. 2011; Bocken et al. 2014; Bolton & Hannon 2016). These translate into severe financing problems since in these stages high-risk finance needs a rapid market development in order to refinance their investments (Kenney & Hargadon 2012; Marcus et al. 2013). To overcome the 'valley of death', in addition to continuous public investment in R&D and commercialisation (Kimura 2010), production support measures, such as production tax credit, should be enacted (Barradale 2010; Haley & Schuler 2011; Komor & Bazilian 2005) which helps financiers such as VC, business angels overcome scale-up problems (Bürer & Wüstenhagen 2009; Kenney & Hargadon 2012; Marcus et al. 2013).

Many clean technologies depend on energy savings which are foiled by artificially low energy prices due to subsidies for fossil-fuels (Jaffe et al. 2005; Jaffe & Stavins 1994; Jefferson 2008; Sandén & Azar 2005; Sovacool 2008). This translates into long timescales for turnover especially in energy-supply and energy end-use technologies and for development and demonstration of new energy technologies that render these investments unattractive for available finance instruments (e.g. business angels, VC, crowdfunding) (Bruton et al. 2015; Haley & Schuler 2011; Kenney & Hargadon 2012; Vasileiadou et al. 2015).

In response, demand-pull policies should support consumption (Haley & Schuler 2011; Sartorius 2008; Montalvo 2008; Tsoutsos & Stamboulis 2005). These could take the form of tax breaks and incentives for entrepreneurs to gain a competitive advantage vis-à-vis incumbents which has been valued by VC investors (Bürer & Wüstenhagen 2009;

Komor & Bazilian 2005). As market formation becomes imperative in this stage, policy makers should connect market formation and policy incentives through neutral support as more market segments are targeted (del Río & Bleda 2012; Dewald & Truffer 2011) which again corresponds with a market based approach to sustainable innovation. Lead market creation on the other hand (Horbach et al. 2014; Beise & Rennings 2004) and procurement as a mission-oriented innovation policy might also a viable policy option (Edquist & Zabala-Iturriagagoitia 2012; Bürer & Wüstenhagen 2009; Foxon et al. 2005). As long as financiers understand the strategy behind the support mechanisms they are willing to accept a degree of regulatory dependency and policy risk (Lüthi & Prässler 2011; Lüthi & Wüstenhagen 2012).

Throughout the niche-market and fully commercial phases, demand articulation failures occur. The absence of orienting and stimulating signals from public demand and a lack of demand-articulating competencies in the private sector further aggravate the problem (Markard & Truffer 2008; Weber & Rohracher 2012). Market criteria (such as expected demand etc.) rank among the priorities of investors or lenders, hence absence of demand proves to be severe financial obstacle (Bocken 2015; Petty & Gruber 2011).

Policy makers could support these phases through subsidies (e.g. refund schemes) could accelerate the diffusion in the short run (Cantono & Silverberg 2009; Fischer & Newell 2008; Montalvo 2008; Komor & Bazilian 2005) although they might repel investors due to high policy risk (Polzin et al. 2015; Wüstenhagen & Menichetti 2012). Apart from withdrawing subsidies for fossil fuel based technologies (Jefferson 2008; Sovacool 2008; Jaffe & Stavins 1994), taxes on products, emissions or fossil fuels (Acemoglu et al. 2012; Popp 2010; Fischer & Newell 2008; Mickwitz et al. 2008; Freeman 1996) or stable tax incentives for private innovation further stimulate competitiveness with fossil-fuel based technologies and thus encourage professional (institutional) investors, private equity and banks to commit larger funds in a market-based environment (Polzin et al. 2015; Wüstenhagen & Menichetti 2012). Furthermore policy makers should focus on the product standards and demand-generating effects of regulation as well as an articulation of quality requirements (Perez 2013; Rennings & Rammer 2011; Mickwitz et al. 2008; Brown 2001; Horbach et al. 2013) which is also favoured by financiers due to their political reliability (Lüthi & Prässler 2011; Lüthi & Wüstenhagen 2012; Polzin et al. 2015). Specifically for renewable energy technologies, feed-in tariffs (del Río & Bleda 2012; Johnstone et al. 2010; Lewis & Wiser 2007; Dinica 2006) and renewable obligation certificates or quota models such as renewable portfolio standards (Carley 2009; Lewis & Wiser 2007; Mitchell et al. 2006) have been proven to accelerate the diffusion (Bergek & Jacobsson 2010; Bird et al. 2008; Menanteau et al. 2003) and also favour early and late stage investments (Bürer & Wüstenhagen 2009; Polzin et al. 2015; Rodríguez et al. 2015).

Financial barriers - Mobilise public and private investment

Overarching genuine financial barriers i.e. barriers that relate to financial markets consist of the information asymmetries and bounded rationality as financiers typically do not possess technological or political know-how to evaluate risks and returns of investments in innovative clean technologies (Olmos et al. 2012). Price, volume and balancing risks are the main underlying financial barriers (Bergek et al. 2013; Mitchell et al. 2006).

Olmos et al. (2012) diagnose underinvestment in clean energy R&D and analyse which instruments maximise the amount of socially valuable clean RD&D by leveraging private sector funding as far as possible within each stage of project maturity. They suggest public loans, or guarantees provided by public bodies backing private loans, along with public investments in the equity of innovating companies depending on the characteristics of the research projects.

Financial barriers are most prevalent in the demonstration, pre-commercial and commercial phases. Scholars diagnose capital market imperfections (Jacobsson & Karltorp 2013; Leete et al. 2013; Sanstad & Howarth 1994) for innovative clean technologies as VC is missing or is unsuitable for certain investments (Leete et al. 2013; Kenney & Hargadon 2012; Randjelovic et al. 2003). Financing production and scale-up proves to be a challenge (Brown & Hendry 2009; Hendry et al. 2010).

These barriers could be mitigated by either directly investing into infrastructure and companies or by incentivising private investments into clean technologies. Thus, combined public and private investment and state investment banks represent vehicles of direct intervention (Mathews et al. 2010; Mazzucato 2013). Improving positive expectations of future market opportunities, encouraging private capital into the less mature and difficult-to-finance technologies and the regulation of financial markets to redirect financial capital in productive investments represent incentives for financiers (Foxon & Pearson 2008; Jefferson 2008; Perez 2013; Johnstone et al. 2010). Direct financing, investment enabling, and fiscal policies represent a powerful policy mix to address financial barriers (Perez 2013; Foxon et al. 2005; Brown 2001). Specific measures during the commercialisation phase could include the creation of public-private-partnership (PPP) VC funds or statutory obligations, grants or capital-expenditure, and fiscal incentives such as tax breaks for investors (Bürer & Wüstenhagen 2009; Foxon et al. 2005; Mathews et al. 2010).

Obstacles in the diffusion stages include slow capital stock turnover and a corresponding long payback period which relates to capital intensity, especially high upfront investments that hinder the ability to finance by institutional investors i.e. private and public equity or mezzanine capital. Similarly firms are unsuccessful in obtaining credit for investments (Jacobsson & Karltorp 2013; Leete et al. 2013; Lüthi & Prässler 2011; Schleich 2009). To support the fully commercial phase, governments adjust the institutional environment to minimize regulatory and political risks (Chassot et al. 2014; Haley & Schuler 2011; Polzin et al. 2015; Wiser & Pickle 1998). Governments should also consider establishing PPP private equity funds to leverage investments in larger infrastructure or mature cleantech companies (Mathews et al. 2010).

Own representation. Framework adapted from Auerswald & Branscomb (2003); Bürer & Wüstenhagen (2009); Wüstenhagen & Menichetti (2012); Bocken (2015)

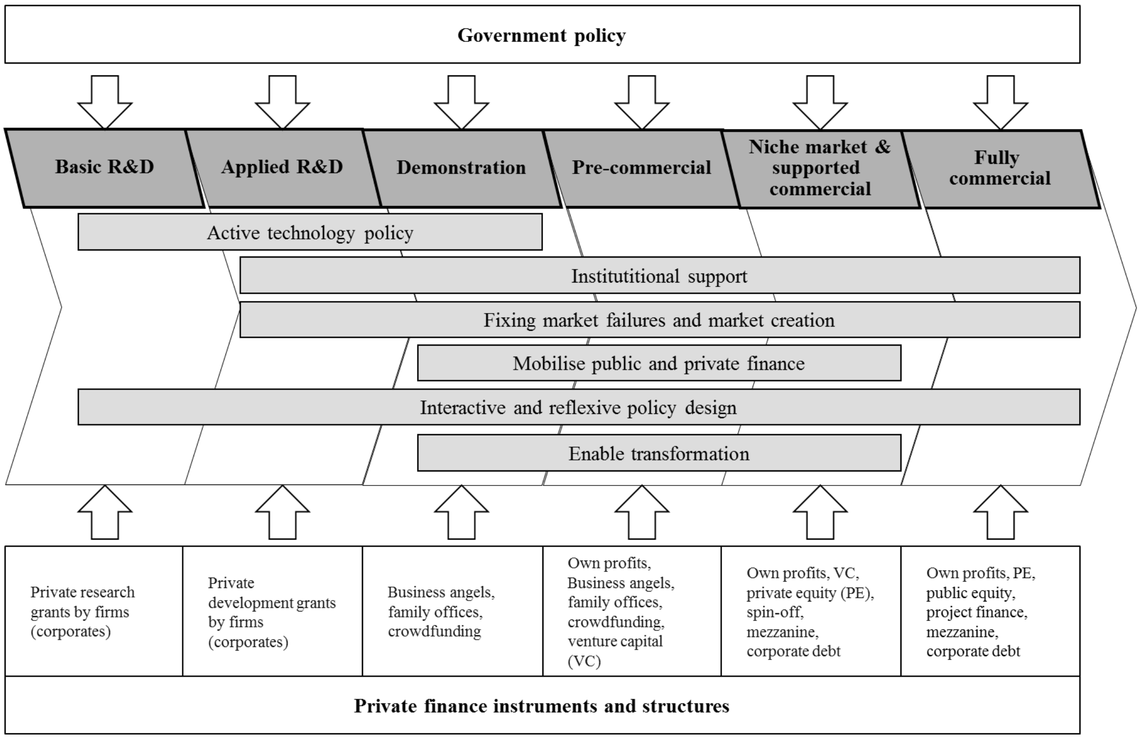

Figure 2: Policy responses to facilitate the financing of low-carbon innovation

Political barriers – Interactive and reflexive policy design

Political barriers directly relate to competencies and mandates of policy makers that engage in the innovation process for clean technologies. Policy coordination failures occur (Weber & Rohracher 2012; del Río & Unruh 2007; Negro et al. 2012). These include the lack of multi-level policy coordination across different systemic levels (e.g. regional–national–European or between technological systems), the lack of horizontal coordination between STI policies and sectoral policies (e.g. transport, energy, agriculture) as well as the lack of vertical coordination between ministries and implementing agencies which leads to deviations between strategic intentions and operational policy implementation (Negro et al. 2012). At the intersection between public and private actors, scholars reveal missing coherence between public policies and private sector institutions, especially financiers. A lack of temporal coordination also results in mismatches related to the timing of policy interventions (Weber & Rohracher 2012; Geels 2010; Agnolucci 2008). For example in later commercialisation stages, inefficient allocation of planning and authorisation competencies have been highlighted (Friebe et al. 2014; Steinbach 2013; del Río & Unruh 2007). The policy coordination failures, when perceived by potential financiers and their instruments lead to an increased consideration of policy risk for their investments and a withdrawel of investments (Bürer & Wüstenhagen 2009; Lüthi & Wüstenhagen 2012; Wüstenhagen & Menichetti 2012; Demirel & Parris 2015). With regard to administrative barriers, a single authority planning, authorisation and regulation competencies may abolish the existing lack of coordination, and stricter administrative time-limits and sanctions could accelerate the development of complementary assets, such as infrastructure which reduces financing risks for the infrastructure itself and corresponding technologies (Friebe et al. 2014; Steinbach 2013).

Reflexivity failures occur which pertain to the insufficient ability of the system to monitor, anticipate changes and involve actors in processes of self-governance, as well as provide spaces for experimentation and learning (Weber & Rohracher 2012; Negro et al. 2012). Correspondingly, policy makers do not implement adaptive policy portfolios to keep options open and deal with uncertainty (Weber & Rohracher 2012; Geels 2010; Rao & Kishore 2010). The reflexivity typically does not include implications for the finance environment which leads to potentially severe losses and risk-aversion (Chassot et al. 2014; Polzin et al. 2016).

Weber and Rohracher (2012) and Stilgoe et al. (2013) also refer to a directional failure, which comprises a lack of shared vision regarding the goal and direction of the transformation process, the inability to coordinate distributed agents involved in shaping systemic change and insufficient regulation or standards to guide the direction of change. This vision and corresponding activities are needed to convince financial market actors to commit (larger) investments (Polzin et al. 2015; Demirel & Parris 2015; Wiser & Pickle 1998).

To address these political barriers, scholars suggest a number of overarching design features for low-carbon innovation policy. First of all, policy design should adhere to certain criteria such as flexibility, stability, targeting, stringency and predictability (Leete et al. 2013; Arent et al. 2011; Foxon & Pearson 2008; Mickwitz et al. 2008; Negro et al.

2012; Rao & Kishore 2010; Wiser & Pickle 1998). These criteria contribute to reducing political risk for financiers at all stages in the innovation cycle (Wüstenhagen & Menichetti 2012; Criscuolo & Menon 2015; Demirel & Parris 2015). Scholars researching the financing for low-carbon innovation suggest a portfolio of policy measures at different stages in the innovation cycle (Bürer & Wüstenhagen 2009; Polzin et al. 2015; Criscuolo & Menon 2015). Second, the timing of policy and inter-temporal consistency of the policy measures are important (van den Bergh 2013; Veugelers 2012; Loiter & Norberg-Bohm 1999; Negro et al. 2012) which requires the reflection upon which private financial instruments are available and how these could be leveraged. Third, policy regimes should be evaluated according to outcome indicators of technology, actors and institutions as well as societal and environmental impact (Neij & Åstrand 2006; Jaffe et al. 2005). This could be done using an interactive approach to policy design which targets market design and implications as well as stakeholder involvement (Enzensberger et al. 2002). During this process, financiers as major stakeholders should be involved (Polzin et al. 2016).

Transformation barriers – Strategic niche management and niche creation

Drawing from the literature on system transitions, scholars highlight transition problems (Foxon & Pearson 2008; Markard et al. 2012; Altenburg & Pegels 2012; Nill & Kemp 2009; Farla et al. 2012). Lock-in problems are comprised of the aforementioned technological, economic and institutional lock-ins such as the missing development of niches, hinder widespread adoption (Smink et al. 2015; Jacobsson & Lauber 2006). Hockerts and Wüstenhagen (2010) state that the interaction between incumbents and new entrants provides the opportunity to transfer eco-innovation from niches into the mainstream markets as they can deploy own funds to push low-carbon innovations into the markets. However, the power relations across the networks of actors involved in a regime typically prevent a systemic change (Kern & Smith 2008; Smith et al. 2005; Negro et al. 2012). As financial market actors, especially banks and institutional investors are involved financing both new entrants and established actors they are prone to be locked-in to existing technologies as they provide the necessary stable returns (Bocken 2015). Although alternative forms of financing such as business angels and VC on average take greater risks they do not invest with a longer time horizon necessary to drive a transformation (Kenney & Hargadon 2012; Marcus et al. 2013; Mazzucato 2013; Bocken 2015). To respond to these barriers, Coenen and Diaz Lopez (2010) compare different approaches to system failures for eco-innovations and conclude that a combination of the focus on global economic competitiveness and a sustainable transition of society would be most fruitful. Especially the open competition between single low-carbon technologies and a level playing field with incumbent technologies proves beneficial to mobilise private finance (Jefferson 2008; Mathews et al. 2010; Bocken 2015).

During the commercialisation and diffusion stages, Weber and Rohrbacher (2012) add socio-technical barriers that impede the transition. These comprise behavioural and cultural barriers such as social interests of the incumbents (i.e. firms developing and applying fossil-fuel based technologies) and the legitimacy of the new technology (Smith et al. 2010; Sovacool 2009; Negro et al. 2012). These power dynamics severely play out in the financing environment as financiers are embedded into and survey societal changes. Mission-driven financiers play the role of enablers, however the majority of private investors or lenders lack the vision for sustainability (Masini & Menichetti 2012; Mazzucato 2013). To overcome the gap between demonstration, pre-commercial and supported commercial phases, early niche market creation and strategic niche management is suggested to challenge incumbents and regime technologies (Smink et al. 2015; Kimura 2010; Smith et al. 2010; Kern & Smith 2008; Foxon & Pearson 2008; Jacobsson & Lauber 2006; Nill & Kemp 2009) which also provides the opportunity for financiers to solve the lock-in (Polzin et al. 2016; Schmidt 2014). To accelerate this process new technologies need to be integrated into existing systems (Arent et al. 2011).

Discussion

Addressing barriers to low-carbon innovation and consequences for finance

At first, this article shows that abstract failures relating to financing low-carbon innovation could only be addressed on a very concrete level. Reconciling literature streams provides a holistic understanding of the public-private interplay in the innovation-policy-finance nexus for clean technologies. This article complements earlier work that focuses on the abstract failures to innovation on a systemic level (Weber & Rohracher 2012; Edquist 2011; Klein Woolthuis et al. 2005; Negro et al. 2012) as well as on concrete technology oriented research (Kley et al. 2011; Foxon & Pearson 2007; Köhler et al. 2010; del Río & Unruh 2007). More specifically it shows by adding a temporal perspective that barriers to low-carbon innovation have different effects on the innovation process along the technology life cycle. Connecting the abstract failures and tangible barriers has been missing throughout the literature (Newell et al. 2006; van den Bergh 2013; Dewald & Truffer 2011).

A combination of factors such as financial, economic, institutional and transition barriers slows down the development, commercialisation and diffusion of clean technologies and the overall technological transformation (Iyer et al. 2015). These factors result from the interplay between private actors and governmental engagement in the form of science, technology and innovation (STI) policy and regulation along the innovation process (Wüstenhagen & Menichetti 2012; Mathews et al. 2010; Foxon et al. 2008). Advancing systems thinking in the field of eco-innovation as argued by Jacobsson & Bergek (2011) and Foxon & Pearson (2008) is crucial to address barriers in the transition from the demonstration stage towards the pre-commercialisation stage, and between the pre-commercialisation and supported commercialisation stage (scaling) (Foxon et al. 2005; Foxon & Pearson 2008). This article differentiates possible policy measures along the innovation cycle to implement this transition.

A complex set of barriers revolves around the question of how to finance companies, projects and infrastructure based on low-carbon innovation (Polzin et al. 2016). Clean technologies exhibit higher uncertainty, regulatory dependency and capital intensity, which makes them unattractive for private financiers as these possess limited abilities to screen potential targets (Bocken 2015; Kenney & Hargadon 2012; Randjelovic et al. 2003; Horbach et al. 2013). In consequence, this leads to a thin financial market especially for eco-innovation all along the innovation cycle (Dahlstrand & Cetindamar 2000; Nightingale et al. 2009). A combination of technological barriers (technological uncertainty) combined with economic barriers (capital intensity), institutional (regulatory environment, information asymmetries), and political barriers (inconsistent support) contribute to thin financial market for low-carbon innovation all along the innovation cycle (Iyer et al. 2015; Kenney & Hargadon 2012; Mazzucato 2013; Nightingale et al. 2009). Thus addressing these barriers and maximising private investments requires an understanding of the logic behind financiers' perception of the innovation process for clean technologies (Bürer & Wüstenhagen 2009; Kenney & Hargadon 2012; Marcus et al. 2013; Polzin et al. 2015; Wüstenhagen & Menichetti 2012). This perspective includes a risk and return calculus, a focus on commercialisation and possible influences of STI and the regulatory environment on the financing eco-system of novel technologies.

Most of the studies analysing the relationship between finance and innovation (with a few exceptions), focus on the generation and commercialisation of technologies, mainly highlighting private equity and particularly VC as a suitable solution for certain types of companies and technologies (Bürer & Wüstenhagen 2009; Kenney & Hargadon 2012; Leete et al. 2013). However, research that takes into account structures and policy mechanisms for low-carbon innovations in the early and later stages is still missing. Depending on the actual step in the innovation cycle, financing solutions for innovative companies and complementary infrastructure exhibit different characteristics (Jacobsson & Karltorp 2013; Leete et al. 2013; Mathews et al. 2010).

Holistic view on financing low-carbon innovation

This article systematically and holistically treats the financing of development, commercialisation and diffusion of clean technologies and therefore goes beyond existing work that addresses barriers to low-carbon innovation (Foxon & Pearson 2008; Negro et al. 2012; Eleftheriadis & Anagnostopoulou 2015). To accelerate the commercialisation and diffusion of clean technologies, policy makers need to address the genuine financial barriers (i.e. related to capital markets) but also the underlying technological, institutional, political and economic barriers as well as transformation barriers that have consequences for the finance environment. Structures to channel the financial resources into companies, projects and infrastructure as well as the policy measures aiming at supporting this process need to be tailored to the actual stage in the technological lifecycle and the corresponding market.

By focusing on tangible barriers that relate to finance along the innovation cycle, the article revealed the tremendous potential of connecting public support with private finance in an effective and efficient manner. Thin markets for finance especially present huge opportunities in accelerating the innovation process for clean technologies. These findings are supported by other researchers (Mowery et al. 2010; Hargadon 2010; Kenney & Hargadon 2012; Huberty & Zysman 2010; Wiser & Pickle 1998). Policy measures targeting the critical stages (such as the 'valley of death') should start earlier in the innovation process to allow for an efficient transition between the phases. Thus, particularly in the case of eco-innovation, more systemic efforts are needed to balance regulation, innovation and complementary financial mechanisms.

Scholars acknowledge that the promotion of generation, commercialisation and diffusion of low-carbon technologies should involve support for R&D, demonstration and deployment as well as the creation of markets (Foxon et al. 2008; van den Bergh 2013; Iyer et al. 2015). Following the analysis, this article proposes an adaptive policy design to address specific barriers to low-carbon innovation along the innovation cycle for the technology which includes anticipating future steps in the technology development and commercialisation process and having the corresponding policy instruments ready to support a seamless transition between the stages and gaps and correspondingly mobilise private finance. This requires strong signals from public actors towards research, industry and financiers (Mazzucato 2013; Wiser & Pickle 1998). In order to apply the multitude of policy instruments upon a complex web of barriers to clean technology innovation, policy makers need to develop the necessary skills such as in-depth knowledge of relevant technological systems, co-ordination skills, patience, flexibility (Arent et al. 2011; Jefferson 2008; Veugelers 2012; Negro et al. 2012; Rao & Kishore 2010; Agnolucci 2008). In sum, policy makers need to incorporate the 'adequate' distribution of responsibilities between private (especially financiers) and public actors into their decision making. Structures of public-private-cooperation need to be found that allow transparency, partnering and risk sharing between public and private actors.

Implications for policy makers

First, when addressing barriers to low-carbon innovation, policy makers need to pay attention to the actual stage in the innovation cycle and the corresponding market to tailor their policy intervention while maximising private investments. Considering the interaction between institutional, economic and transformational barriers while accounting for the political barriers such as coordination and reflexivity failures has implications for the financing of clean technology firms, projects and infrastructure. Economic, technological and knowledge barriers translate into private under-investments in clean R&D in the early stages. Changes to support mechanisms and missing complementary assets (such as infrastructure) significantly impact the ability to obtain private finance during commercialisation. Regulatory changes and power of incumbents applying fossil-fuel based technologies hinder private financiers from investing even in mature technologies due to an uncertain market outlook.

Second, in order to mobilise private investments, policy makers need to reflect on the implication for the risk and return calculus of financiers before designing a market intervention and deciding which kinds of innovation to support. The ability of private financiers to allocate resources for clean technologies should not be hampered by policy intervention. Thus engaging in an active collaboration with private financiers is crucial to provide a mutual understanding of the innovation process for clean technologies, its potential risks and future market opportunities, thereby reducing information asymmetries. This collaboration should start at the verge towards the commercialisation of a technology by designing research partnerships that tackle these financial questions together with technology development. Relevance, possibilities and advisability of including questions related to finance need to become central to STI policy.

Third, policy makers should start with a clear strategic vision in the various clean technology sub-sectors and encourage private investments, synchronising STI policy and corresponding regulation, and providing direct fiscal and financial incentives as well as market based incentives to accompany a technology stream or sector from the early stages towards maturity. To maximise private investments, regulatory changes need to be adjusted according to technological improvements. Embedding these changes in a transparent consultation process involving policy makers and private actors provides the necessary reliability vis-à-vis financiers.

Fourth, on the one hand policy makers need to evaluate how the barriers along the innovation cycle of clean technologies are perceived by financiers and which incentives or regulation targeting both real economy and financial markets could foster their engagement. On the other hand, financiers should sharpen their competencies with regard to concrete technologies, business models and policy initiatives to develop new methods of financing innovative clean technologies. Policy makers could assist this process of by making the technology development process more transparent, i.e. identifying future finance needs and thus transforming uncertainty into calculable risk and returns.

Limitations

Although this literature reviews aims to be transparent and replicable, there remain some limitations to the methodology used. While the databases do not contain all the relevant studies, they have nevertheless allowed building a sample that is representative of the work throughout the selected literature streams. The barriers lined out here exhibit many different consequences resulting in the slow uptake of low-carbon innovations. This article focuses on implications of barriers to low-carbon innovation for financiers which, according to several scholars, represents a promising line of research (Kenney & Hargadon 2012; Jacobsson & Karltorp 2013; Wüstenhagen & Menichetti 2012; Mathews et al. 2010).

Future research

This article suggest to further research the interplay between finance and innovation as the transformational aspect of finance with regard to innovation processes has been under-researched. Financiers play a special role in transitions as they accumulate the necessary resources for large scale investments (Perez 2013; Kenney & Hargadon 2012; Hargadon 2010). Also the overall link between finance and innovation has been neglected throughout the innovation systems literature (Dosi 1990; O'Sullivan 2006; Perez 2002). Table 1 shows possible avenues for future research in the domain of financing eco-innovation and adjacent areas.

Table 1: Selected avenues for future research

Area of study	**Under-researched aspects**
Financing eco-innovation	Advanced private financing options (beyond) VC for the commercialisation and diffusion phases

	Investor behaviour regarding cleantech
	Financial regulation and support for cleantech
Effective and efficient policies for financing eco-innovation	Combination of support and financial instruments
	Comparison of policy instruments to support the diffusion
	Transformational policy instruments (governance)

Financing eco-innovation

Initial research has been done to consider financing in the early stages beyond basic research grants such as public investments or loans, however public and private instruments in the transition towards demonstration, pre-commercial and supported commercial phases have not been analysed yet (Dinica 2008; Mathews et al. 2010; Mazzucato 2013; Olmos et al. 2012). Mechanisms to leverage the financiers capabilities are also lacking (Foxon & Pearson 2008; Jefferson 2008). For instance, to share the risks associated with early stage technologies and the tendency of private VC to avoid the early stages, especially for low-carbon innovation, PPP-VC might be a viable structure (Mathews et al. 2010). Initial analysis of the (non-financial) barriers suggest that these interact and result in consequences for financing (Bergek et al. 2013; Friebe et al. 2014; Wüstenhagen & Menichetti 2012). Accordingly scholars call for an advanced consideration of risks and policy instruments that adjust the risk/reward ratio to successfully commercialise clean technologies (Foxon et al. 2008; Lüthi & Prässler 2011).

On the national level, PPP fund structures that provide VC and private equity as well as project finance could be explored to complement risk averse private capital in the early and later stages (Mathews et al. 2010). In addition, crowdfunding platforms as a structure for micro-finance of companies or projects that develop and apply innovative clean technologies would be interesting for further research (Bruton et al. 2015; Lehner 2013; Lehner & Nicholls 2014; Vasileiadou et al. 2015). On an international level, research on structures to channel public and private money into clean technologies, such as the Green Climate Fund should be evaluated with regard to their innovation effect to foster long-term green growth (Friebe et al. 2014; Mathews et al. 2010).

Effective and efficient policies for financing eco-innovation

To address barriers to low-carbon innovation, policy makers are presented with a number of instruments along the innovation cycle. Prior research suggests that demand could be catalysed by an open industry knowledge base for rapid diffusion (Hargadon

2010; Huberty & Zysman 2010; Negro et al. 2012). However, combinations of instruments have not been evaluated on a system level or with concrete relation to technologies. Hence research on a policy mix to foster long-term low-carbon innovation systems including transformational elements proves useful in order to give recommendations on how the ongoing clean technology revolution could be governed (Flanagan et al. 2011; Guerzoni & Raiteri 2015; Kern & Smith 2008; Rogge & Reichardt 2016).

Especially the demand-side measures should be evaluated with regard to their effectiveness, efficiency and consequences for finance to achieve synergies between public and private instruments (Haley & Schuler 2011; Sartorius 2008; Tsoutsos & Stamboulis 2005; Wüstenhagen & Bilharz 2006). A second avenue of research addresses investment-enabling and fiscal policies which have been neglected in current literature (Perez 2013; Foxon et al. 2005; Brown 2001). Furthermore the link between policy instruments, regulation of financial markets and private finance mechanisms could be analysed regarding complementarity and synergies.

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