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Mobilizing private finance for low-carbon innovation – A systematic review of barriers and solutions

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ABSTRACT

This paper analyses the field of innovation studies regarding barriers to low-carbon innovation and consequences for finance (investment and divestment) and contributes to a more holistic understanding of the underlying mechanisms. A combination of technological barriers combined with economic barriers, institutional and political barriers contribute to sub-optimal low-carbon investment all along the innovation cycle. Policy makers need to take a systemic approach to enable the redirection of diverse private financial sources. Instruments range from cutting 'dirty' (R & D) subsidies and support for clean technology innovation and diffusion, levelling the institutional playing field and making risks of high-carbon and low-carbon technologies transparent to providing a consistent but adaptive long-term transition strategy. This would allow financiers to gradually shift their investments away from high-carbon mainstream markets and scale low-carbon technology niche-markets. However financiers also need to sharpen their competencies with regard to new clean technologies and markets.

1. Introduction

Global climate change has been recognized amongst the biggest 'grand challenges' facing humanity in the 21st century. McGlade and Ekins [1] estimate that to keep global warming below 2 °C up to 2050, approximately 35% of known oil reserves, 52% of gas reserves and 88% of coal reserves cannot be used. There is widespread consensus among policy makers, businesses, the scientific community and wider society that the transition towards a low-carbon economy by decoupling economic activity from the use of finite resources is imperative for sustainability [2–7].

A critical element in this transition is the development and diffusion of clean technologies (eco-innovation) [2,8–11][1] with simultaneous withdrawal from carbon-intensive technologies based on fossil fuels [15,16]. This process is hampered by many 'barriers', relating both to the inherent characteristics of innovation and technological change, and to environmental externalities [13,17].[2] One of the most salient barriers to low-carbon innovation identified by scholars and experts is the financing environment [e.g. 19–25].

In 2014, climate finance accounted for 391 USDbn of which private institutions provided 243 USDbn [25]. Investment in Research & Development (R & D), commercialization and diffusion of clean technologies still remains below the required level to limit warming to 2 °C despite central banks providing large amounts of liquidity through quantitative easing [26]. Recent investment trends show decreasing finance dedicated to clean technologies and a corresponding an increase in risk aversion from financiers [9,10,27–30]. However, clean technologies necessitate significant investment in companies, projects and infrastructure, with estimates ranging from 700 USDbn to 1–2% of global GDP (740 USDbn to 1.48 USDtn = 1480 USDbn) [5,31,32]. These numbers far surpass government funding possibilities [13,29,33,34].

Institutional investors such as insurance companies, pension funds and even banks have invested and lent extensively to fossil fuel-based endeavors, building high-carbon portfolios that now pose a 'value at risk' [16,35,36]. Given the Paris COP21 agreement these investments are going to lose at least part of their value by 2050, creating a 'carbon bubble' [37–39]. New fossil fuel based capacities are still being created and financed today, and Fig. 1 reveals current investment flows into both high-carbon and low-carbon energy technologies. To have credible portfolios in the future and prevent financial system instability, investors and lenders must transition into growing low-carbon

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[1] Low-carbon innovation can be defined as the 'invention, commercialization and diffusion of technologies that reduce carbon emissions and/or other environmentally negative impacts and thus contributes to sustainability' [12–14]. Throughout the course of the analysis eco-innovation, low-carbon innovation, innovation in clean technologies and environmental innovation will be used interchangeably.

[2] 'Barriers' are blocking mechanisms, obstacles or hampering mechanisms, that prevent clean technologies from being commercialised and diffused which in turn inhibits the financing environment [13,18–22].

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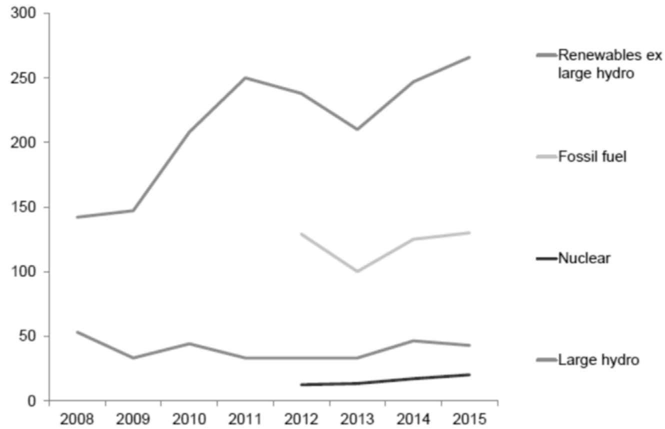

Fig. 1. Investments into renewable energy and fossil fuels 2008–2015 (in USDbn) Source: [30].

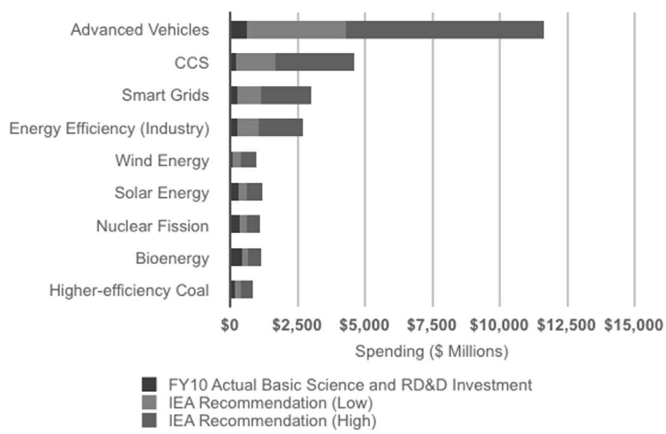

Fig. 2. IEA Recommended Energy Basic Science and RD & D Investment compared to fiscal year 2010 actual basic science and RD & D spending levels, US example (in USDmn) Source: [85].

markets, and divest from high-carbon technologies to avoid 'stranded assets'[3] [26,41–43].

Yet there are surprisingly few systematic reviews on financing this 'sustainability transition' [26,35,44]. This article's systematic review of the knowledge base, in a first step, strives towards a more comprehensive understanding of the peculiarities that eco-innovations encounter with regard to finance. In a second step it explores how policy makers can address these barriers and enable the redirection of private finance from fossil fuels to clean technologies.

To address these aspects, this paper is structured as follows: Section two describes the methodology used to assemble the knowledge base, which is then reviewed in the following chapters. Section three draws on a process framework for eco-innovation and organizes barriers accordingly, focusing on consequences for finance that affect both investment and divestment and addresses possible policy solutions. Finally, section four discusses findings and implications.

2. Methodology

The methodological approach to assemble the knowledge base has deliberately been kept simple to portray a relatively broad topic and do justice to the expected heterogeneity in the literature. The goal was to identify a representative base of articles that describe barriers to low-carbon innovation which have consequences for finance and possible policy solutions in a narrative literature review. It is not intended to be comprehensive, but nor does it ignore critical theoretical perspectives. The articles were identified and classified, the texts analyzed and mapped into a theoretical framework [45]. Eco-innovation research encompasses a variety of perspectives and disciplines, including innovation systems [46], transition studies [47], climate, environmental and ecological economics [48–50], energy economics and policy [51,52] and climate science [36,53]. To gain a more comprehensive picture of the technological, economic and institutional processes surrounding eco-innovation, an interdisciplinary approach is adopted thereby enabling the integration of hitherto separate literature and debate streams.

The literature search required certain choices. For purposes of quality, the first choice was to include only published seminal books and peer-reviewed articles [54]. According to Hunter and Schmidt [55] this does not lead to an 'availability bias' for empirical studies because if the number of articles is sufficiently large, the direction of the published and unpublished results tend to be the same. The second choice was to use five scientific search engines that are widely used in the community of innovation scholars to carry out keyword searches [e.g. 56]. The search engines reviewed include Business Source Complete, Science Direct, EBSCO, Emerald and Google Scholar. Finally a database for all 173 peer-reviewed papers was developed, containing author(s), title, publication, main argument, chain of arguments, empirical or conceptual setting and keywords. The articles have been classified according to the main argument and keywords section, and an overview of the knowledge base can be found in Table A.1 (Appendix A) [45].

Although this literature reviews aims to be transparent and replicable, there remain some limitations to the methodology used. While the database does not contain all the relevant studies, they have nevertheless allowed building a sample that is representative of the work throughout the selected literature streams.

3. Findings

The stylized 'innovation-finance-policy-chain' involves public actors and private financiers. *A priori* financiers face the trade-off between commitments to low-carbon vs. high-carbon innovation and deployment [15,57]. Policy makers possess a range of options to encourage the redirection of private finance from 'dirty' to clean innovation and hence to achieve the low-carbon transition [34,58,59]. Fig. 3 shows barriers along the innovation cycle. The categories are not mutually exclusive. In order to advance systems-thinking for low-carbon innovation, this systematic review embraces the overlaps for example between institutional and political barriers or economic and financial barriers. Fig. 5 depicts possible policy responses to address the complex web of barriers discovered earlier.

During the basic and applied R & D stages technologies are developed by public research institutes and universities as well as private firms, both of which supply the necessary finance through grants and subsidies. In the demonstration and early commercialization phase ('valley of death'), private financiers such as business angels, family offices and Venture Capitalists (VCs) invest in start-ups and small innovative firms, whereas large or mature firms deploy internal funds for ongoing R & D and commercialization activities. Technology is sufficiently mature to allow for scale-up towards production which is financed by VC [60,61] or family offices with a long-term investment strategy [62]. Founders also draw from informal capital sources of such as family and friends [18,62]. Recently, crowdfunding has emerged as an alternative way to raise seed finance [62–64]. 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 while banks, private equity investors and internal funds provide financing for production and marketing [62,66]. Additionally

[3] 'Assets that have suffered from unanticipated or premature write-downs, devaluations or conversion to liabilities' [40].

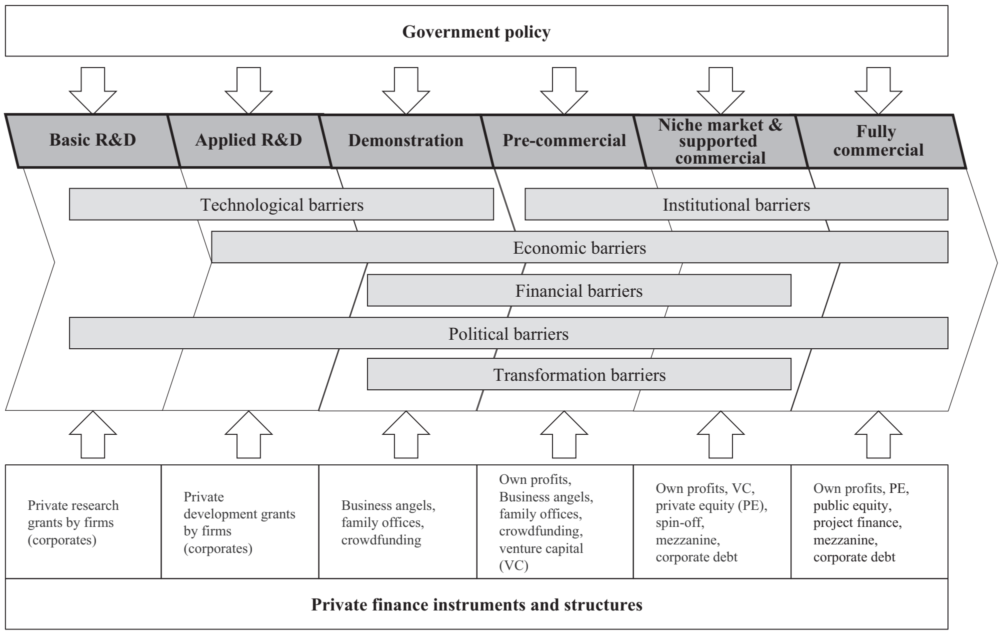

Fig. 3. Barriers at the interplay between private finance instruments and government policies. Own representation. Framework adapted from [18] and [68].

institutional investors finance complementary assets such as projects and infrastructure [67,68].

3.1. Directed technology policy to address technological barriers

The most significant technological barrier facing sustainable innovation is technological lock-in[4] and path dependency. This results from insufficient technological maturity compared to fossil-fuel based technologies and translates into expectations of severe market failures and questionable commercial viability [13,23,70,71]. These developments are persistent due to suboptimal investments by private firms in clean R & D compared to 'dirty' R & D investments (see Fig. 2) [19,66,72].

To break the lock-in and redirect funds into clean research, development and demonstration (RD & D) scholars suggest a long-term technology strategy that is effectively coordinated with demand-side policies [10,73]. Policy makers should strive to increase technological diversity e.g. by integrating environmental policy targets in technology policy and operationalizing them into research programs [9,74–76]. These measures would allow early stage financial instruments such as private RD & D grants and crowdfunding to be used more effectively for clean technologies, reflecting a market-based approach to sustainable innovation many private financiers favor (especially VCs, private equity, business angels and banks) [62,63,77,78]. Furthermore public–private RD & D partnerships between combinations of industry, academia, governmental and non-governmental entities such as SBIR, ATP or ARPA-E[5] overcome competence lock-ins in fossil-fuel-based technologies [79–82]. Adding private financiers to these partnerships could accelerate commercialization of clean alternatives [22,83,84].

Beginning with the demonstration phase, stakeholders perceive technological risks and complexity associated with new clean technologies such as long-term performance [49,86] and adverse salient effects on the socio-economic and natural environments [23,87,88]. Hence missing stakeholder involvement proves a significant barrier since clean technologies often affect a range of stakeholders throughout their development, demonstration and especially diffusion phases e.g. renewables or smart grids being rejected by citizens [89–91]. As informed financiers such as business angels and family offices consider these developments in their risk/return calculations, they refrain from financing companies that are active in the cleantech sectors and continue high-carbon investments instead [62,92].

During these critical phases, demonstration projects, trials and technology transfer programs are strongly suggested to assess and validate feasibility, commercial viability and to rule out emerging reverse salient factors [81,93–95]. Providing these results to private financiers and crowdfunders would reduce information asymmetries and thus facilitate investments [18,60,65,96]. Crowdfunding also distributes risk, thereby tackling performance problems and reverse salients on a smaller scale [63,97].

3.2. Adapting institutions to overcome institutional barriers

Institutional barriers comprise institutional 'lock-ins' associated with changing patterns of behavior, social rules and norms that favor fossil-fuel-based technologies deployed in the last decades [13,14,79,98]. Environmental economists widely suggest a combination of regulation and R & D support as components of the solution [48,51,74,99]. However, to escape institutional lock-ins and related failures, Rennings [14] highlights the importance of systemic approaches.

During the demonstration stage missing physical infrastructure such as power and transport, and scientific infrastructure, such as high-quality universities, research laboratories and technical institutes dedicated to clean technologies represent significant barriers [20,59]. Eco-innovations as systemic innovations depend on complementary, capital intensive assets for their commercialization e.g. in the case of fuel cell mobility [59,71,100–102]. Required infrastructure investments amount to 90 USDtn over the next 15 years, with additional investments of 270 USDbn in a business-as-usual scenario [24]. These private finance mechanisms rely on a long-term horizon with stable returns [101,103]. Existing infrastructure may also need to be discharged and written off [15,42]. Therefore, policy makers should provide support for development of (grid-) infrastructure technologies and other complementary assets to encourage institutional investors to

[4] 'Path-dependency implies that entrenched technologies have a distinct advantage over newcomers, not because they are inherently better, but because they are widely used. In this sense, positive feedbacks lead to technology lock-in' [69].

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

shift their money away from existing high-carbon assets [20,101,103].

When moving towards commercialization, regulatory risk and uncertainty such as unanticipated or recurring policy changes, legal security and duration of administrative processes proves significantly hindering (for an in-depth discussion, see Section 3.5) [28,68,71,104,105]. Previous regulatory regimes aimed at accommodating a fossil-fuel based economy and corresponding technologies [15]. Policy risks represent probably the most direct barrier for an investment, as many technologies and their applications along the innovation cycle directly or indirectly depend on a favorable political environment [68,106]. Consequently the transition towards clean technologies affects all financial instruments although more industry specialized investors such as business angels, VC and family offices might fully understand the regulatory background and can thus evaluate corresponding risks. Banks for example refrain from lending to business overly dependent on regulations as these are easily revocable [18,28,105].

In the diffusion phases, administrative approval and spatial planning can still prevent clean technologies from being deployed [23,99,107]. Similarly negative attitudes and social values or pressure from communities hinder the spread of innovative clean technologies as these divert from the *status quo* [108–110]. Financiers observe societal implications when investing into new sectors and assets and a lack of social acceptance poses a severe reputational risk for them [71,111–113].

To gain broader momentum for technology development and diffusion, policy makers should work with members of different technology-specific advocacy coalitions [114,115], both private capital and various interest organizations, and involve social movements as well as stakeholders [89,116], especially for systemic innovations that require public acceptance (e.g. new energy grids). This open approach involving both professional investors and lenders as well as crowdfunders could help to better understand risks associated with the transition from fossil-fuels to low-carbon technologies [22,63].

3.3. Fixing markets and market creation to address economics barriers

Limited appropriability of the financial returns from cleantech innovation, economic lock-in and corresponding path dependency due to a history of investments in fossil-fuel based technologies represent economic barriers [13,59,68,117]. Fig. 4 describes current and projected capacity additions for clean and fossil-fuel based assets. High-carbon assets are creating 'carbon bubbles' once strict market based or other regulatory measures are established [39]. For example, the total carbon exposure of European financial institutions is estimated to be 1122 USDbn [36–38], and markets have already begun pricing this information in [118].

Innovative clean technologies are subject to externalities since prices for fossil-fuel-based technologies do not incorporate their negative environmental effects [17,118,119]. To address these barriers, policy makers could deploy complementary technology-push mechanisms (R & D policies) and demand-pull deployment policies [120] or a more general internalization of externalities through greenhouse gas emission trading [48,121,122]. The latter is favored by financiers (for a full discussion about financial barriers and solutions, see Section 3.4) [26]. In addition, support mechanisms for 'dirty' innovation need to be eliminated to encourage divestment from high-carbon assets [15,43,117].

In the basic and applied R & D phases, limited appropriability and other externalities translate into a general product and market uncertainty [109,123,124] which results into private underinvestment in R & D [9,80,109,123–126]. R & D subsidies and grants [17,51,57,127] or R & D tax credits [17,128,129] have been suggested to alleviate financial constraints. A complementary reduction of R & D subsidies for fossil-fuel-based technologies shows a strong signal to the financial market actors that a transition towards supporting sustainable innovations is envisioned [75,80,127].

From demonstration to supported commercial stages, scholars regard the main barriers as being costs for deployment, high discount rates on future savings and a corresponding 'waiting' for performance improvements [85,119,130–133]. A lack of business models for clean technologies proves to be equally challenging [56,134,135]. In these stages high-risk finance needs rapid market development to refinance its investments [60,61]. Hence most VC investment remain in the 'old' sectors or information technology [136]. To overcome this 'valley of death', production support measures, such as production tax credit, should be enacted which helps financiers such as VC, business angels overcome scale-up problems [18,60,61,137,138].

Many clean technologies depend on energy savings which are foiled by artificially low energy prices due to subsidies for fossil-fuels [17,69,75,80,119]. Long timescales for turnover especially in energy-supply and energy end-use technologies and for development and demonstration of new energy technologies render these investments unattractive for available finance instruments (e.g. business angels, VC, crowdfunding) [60,63,65,138]. Correspondingly, existing fossil fuel-based energy technologies have long depreciation rates and thus remain in the portfolio of institutional investors for return reasons [41,43,139].

In response, demand-pull policies should support consumption [81,109,138,140]. These could take the form of tax breaks and incentives for entrepreneurs to gain a competitive advantage vis-à-vis incumbent firms which has been valued by VC investors [18,141]. Policy makers should connect market formation and policy incentives through neutral support as more market segments are targeted which again corresponds to a market based approach to sustainable innova-

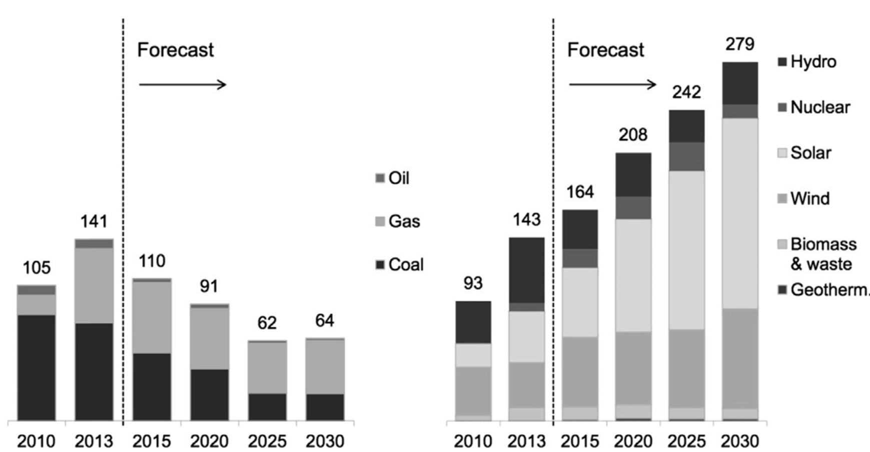

Fig. 4. Current and projected power generation capacity additions 2010–2030 (in GW) Source: [163].

tion [142–144]. Lead market creation [145,146] and procurement as a mission-oriented innovation policy might also be a viable policy option [18,147,148].

Throughout the niche-market and fully commercial phases, the absence of orienting and stimulating signals from public demand, and a lack of demand-articulating competencies in a private sector biased towards fossil-fuel based technologies, hinder the diffusion of clean technologies [149,150]. Market criteria, such as expected demand, are prioritized by investors or lenders, and absence of demand thus proves a severe financial obstacle [26,62,77].

Policy makers could accelerate the diffusion in the short run through subsidies (e.g. refund schemes) [109,141,151] although they might repel investors due to high policy risk [67,68]. Apart from withdrawing subsidies for fossil fuel based technologies [75,80,117,119], taxes on products, emissions or fossil fuels [48,51] or stable tax incentives for private innovation [129,152] further stimulate competitiveness with fossil-fuel based technologies and thus encourage the transition from 'dirty' to clean technologies [67,68]. Product standards and demand-generating effects of regulation, as well as an articulation of quality requirements [33,82,152–154] are also favored by financiers due to their political reliability [28,67,105]. Specifically for renewable energy, feed-in tariffs [95,142,155,156] and renewable obligation certificates or quota models such as renewable portfolio standards [95,157,158] have been proven to accelerate diffusion [159–161] and also favor early and late stage investments [18,67,162].

3.4. (Co-)financing, investment enabling and fiscal policies to overcome financial barriers

Financial barriers 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 between fossil fuels and novel clean technologies [15,42,53,128]. Investing into the wrong technologies now could lead to worthless assets once boundary conditions, such as regulation or demand, change [42].

Olmos et al. [128] diagnose underinvestment in clean energy R & D and analyze which instruments leverage maximum private sector funding within each stage of project maturity. They suggest public loans, or public guarantees backing private loans, along with public investments in the equity of innovating companies.

Financial barriers are most prevalent in the demonstration, pre-commercial and commercial phases. Scholars diagnose capital market imperfections for innovative clean technologies [20,21,164]. VC is missing or is unsuitable for certain investments such as scale-up of asset-heavy production and complementary assets such as infrastructure [21,60,165,166].

These barriers could be mitigated by combined public and private investment and state investment banks e.g. for infrastructure investments [26,167]. 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 [13,33,75,155]. Direct financing, investment enabling policies such as technology support and demand-pull, as well as fiscal policies represent a powerful policy mix to address financial barriers (see also Sections 3.1–3.3) [33,82,148,166]. Specific measures during the commercialization phase could include the creation of public-private VC funds, statutory obligations, grants or capital-expenditure, and fiscal incentives such as tax breaks for investors [18,29,148].

Obstacles in the commercial stages include slow capital stock turnover and a corresponding long payback period. Especially high upfront investments hinder the financing ability of institutional investors and banks [20,21,86,105]. In addition regulatory requirements, such as Basel III and Solvency II, hinder institutional investors and banks from investing in mature low-carbon innovation due to their unfavorable risk/return relationship [26,166].

To support the diffusion, governments should adjust the institutional environment to minimize regulatory and political risks (see Sections 3.2 and 3.5) [27,67,106,138]. To allow institutional investors and banks to invest into clean technologies, risk and equity reserve requirement could be lowered in order to specifically allow for more green finance [26].

At the same time, policy makers need to support the divestment of existing assets (such as coal fired power plants) by obligations to make the carbon footprint of the portfolio transparent and to integrate respective risks into their risk management [36]. IEA estimates that under the 2 °C Scenario, 304 USDbn high-carbon assets will at least partly lose their value by 2035 [168]. To accelerate the divestment process, policy makers could enforce a sustainable investment mandate and portfolio composition on pension funds. Consequently, investment managers either divest or assume an active ownership of fossil-fuel based companies to support their low-carbon transition [15,35,118,139].

3.5. Interactive and reflexive policy design to address political barriers

Coordination failures relate to competencies and mandates of policy makers that engage in the process of innovation-led sustainability transition [59,71,150]. These include the lack of multi-level policy coordination (e.g. regional–national–European or between technological systems), the lack of horizontal coordination between innovation policies and sectoral policies (e.g. transport, energy, agriculture) as well as the lack of vertical coordination between ministries and implementing agencies [59]. Finally, a lack of temporal coordination also results in mismatches related to the timing of policy interventions [150,169,170]. For example later commercialization stages often exhibit inefficient allocation of planning and authorization competencies [71,100,171]. These policy coordination failures are perceived by potential financiers as leading to an increased consideration of policy risk for their investments, a withdrawal of clean investments and a corresponding increase in other investment activities [18,19,28,68]. A single planning authority that possesses authorization and regulation competencies may abolish the existing lack of coordination. Stricter administrative time-limits and sanctions could accelerate the development of complementary assets, such as infrastructure, which makes them more attractive than conventional investments [35,100,171].

Reflexivity failures pertain to the insufficient ability of policy makers to monitor the innovation system, anticipate changes and involve actors in processes of self-governance, experimentation and learning [59,150]. Policy makers do not implement adaptive policy portfolios to keep options open and deal with uncertainty [150,169,172]. Hence, implications for the finance environment are not reflected upon which leads to potentially severe losses, risk-aversion and a reverting back to fossil fuel investments [26,35,139].

Weber and Rohracher [150] and Stilgoe et al. [173] also refer to a directional failure, which comprises a lack of shared vision regarding the goal and direction of the transition process, the inability to coordinate distributed agents involved in shaping systemic change and insufficient regulation or standards to guide the direction of change. A clear vision would allow financiers to shift their assets into low-carbon projects, companies and infrastructure but also to accelerate their divestment activities [19,67,106,139].

To address these political barriers, scholars suggest a number of overarching design features for low-carbon innovation policy. First, policy design should adhere to certain criteria such as flexibility, stability, targeting, stringency and predictability [21,59,106,152,172,174]. These criteria reduce political risk for financiers at all stages in the innovation cycle [19,67,68,175]. Second, the timing of policy measures and their inter-temporal consistency are vital for a seamless transition from fossil-fuel to clean technologies [59,74,120,176]. It also requires the reflection upon existing financial commitments and also allow to evaluate the risk of 'stranded assets' [43,117]. This could be done using an interactive, stakeholder-centered approach to policy design [91], and involving financiers as a major stakeholder group [22].

3.6. Strategic niche management and niche creation to overcome transition barriers

Transition barriers are comprised of lock-in problems and missing development of niches which hinder widespread adoption of novel technologies (see also Sections 3.1–3.4) [6,47,108,177,178]. Hockerts and Wüstenhagen [179] state that the interaction between incumbents and new entrants provides the opportunity to transfer eco-innovation from niches into the mainstream markets as incumbents can deploy own funds to push low-carbon innovations. However, the power relations across the networks of actors involved in a regime typically prevent a systemic change [59,180,181]. As financial market actors, especially banks and institutional investors are involved in financing both new entrants and established actors they are prone to be locked-in to existing technologies as these currently provide stable returns [16,62]. Although alternative forms of financing such as business angels and VC on average take greater risks on average, they do not invest with the longer time horizon necessary to drive a transition [60–62,182]. Open competition between single low-carbon technologies and a level playing field with incumbent technologies proves beneficial to mobilize private finance [29,62,75].

During the commercialization and diffusion stages, behavioral and cultural factors such as social interests of the incumbents and the legitimacy of new technologies impede the transition [59,110,150,183]. These power dynamics play out visibly in the financing environment as financiers are embedded into and observe societal changes. For example required changes in portfolios may lead to abrupt loss of value for certain assets [36]. Mission-driven financiers play the role of enablers, however the majority of private investors or lenders lack the vision for sustainability [87,167,182]. Early niche market creation and strategic niche management is suggested to challenge incumbents and regime technologies [108,177,180,183] and as an opportunity for financiers to solve the lock-in [22,53].

4. Discussion and conclusions

4.1. Barriers to financing low-carbon innovation

Financing the low-carbon transition poses a challenge of unprecedented scale [5,31,32]. For example investments into low-carbon power generation need to triple from 255 USDbn in 2013 to 730 USDbn. Energy efficiency investments even need to rise 8 times from 130 USDbn to 1100 USDbn in 2035 [184]. This article systematically treats the financing of clean technologies across categories of barriers to low-carbon innovation and therefore goes beyond existing work [6,13,58,59,185]. A combination of factors such as financial, economic, institutional and transition barriers slows down clean technology innovation and overall technological transition. These factors result from the interplay between private firms and financiers, and government in the form of science, technology and innovation policy, and regulation along the innovation process [8,29,68,166]. Advancing systems thinking in the field of eco-innovation [13,46] by exploring linkages across barriers and solutions is therefore crucial to transition from high-carbon to low-carbon investments [11,26,35,41].

Technological and economic barriers translate into private under-investments in clean R & D in the early stages [128]. Changes to support mechanisms and missing complementary assets (such as infrastructure) significantly impact the ability to obtain private finance during commercialization [60,104]. 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 [53]. Similarly they hinder reallocation of funds from existing companies, projects and infrastructure towards a new investment category [16,26].

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 [60,62,133,165]. Thus addressing these barriers and maximizing private investments requires an understanding of financiers' perception of the innovation process for clean technologies as well as alternative 'dirty' investment options [18,35,41,61,67,68]. However, financiers should also sharpen their competencies with regard to concrete technologies, business models and policy initiatives to develop new methods of financing innovative clean technologies and shifting funds

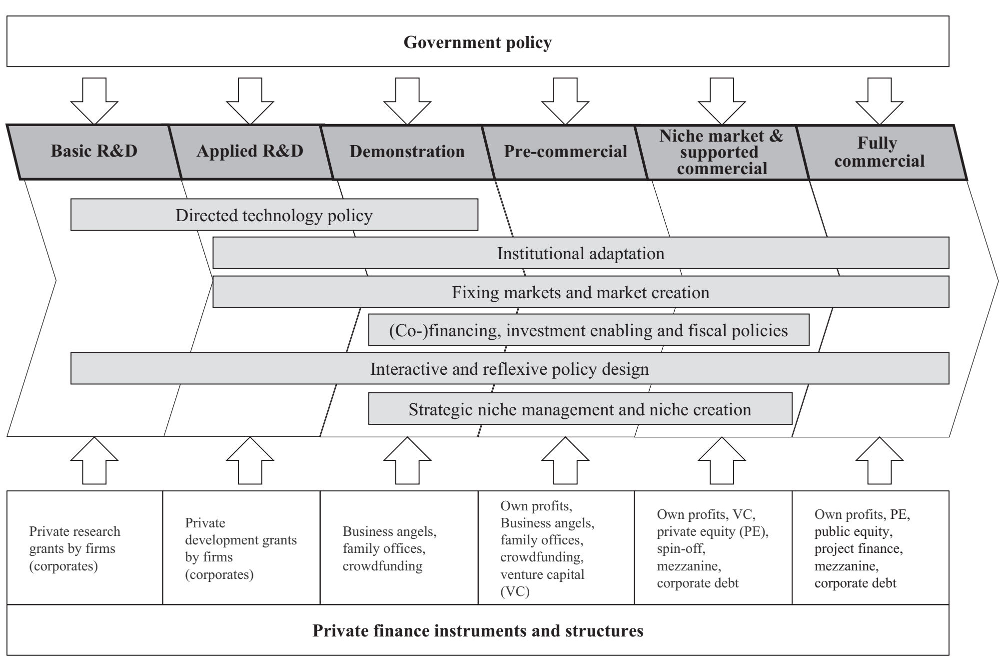

Fig. 5. Policy responses to facilitate the financing of low-carbon innovation. Own representation. Framework adapted from [18] and [68].

away from high-carbon assets.

4.2. Policy mix for enabling the redirection of private finance

To accelerate the commercialization and diffusion of clean technologies, policy makers need to address financial barriers but also the underlying technological, institutional, political and economic barriers as well as transition barriers that have consequences for the finance environment, both new funds and existing investments [15,22,35]. A range of instruments and policy mechanisms for investing in low-carbon innovations in the early and later stages as well as divesting from high-carbon innovation and deployment are needed. Effective measures include public-private RD & D partnerships [10], advocacy coalitions with financiers [22], mission-driven public investments [144,167], demand stimulus [120] and a (RD & D) tax-system reform [17,57,137]. These measures contribute to breaking the 'lock-in' and path-dependency that hold back competitiveness and lead to under-investment in clean technologies [18,22,67,68]. More efforts need to be undertaken to remove advantages for investing in fossil-fuel based technologies such as making ecological and carbon risks transparent and mandating institutional investments into low-carbon projects, companies and infrastructure. These measures facilitate divestment from high-carbon technologies to avoid stranded assets and contribute to a resilient financial sector [16,36,43,139].

A clear strategic vision in the various clean technology sub-sectors and, synchronizing various policy layers encourage private investments into a technology stream or sector from the early stages towards maturity [58,62]. To maximize private investments, regulatory changes need to be adjusted according to technological improvements [67]. Embedding these changes in a transparent consultation process involving policy makers and private actors provides the necessary reliability i.e. by jointly identifying future finance needs and thus transforming uncertainty into calculable risk and returns [22]. This also holds for policy measures effecting existing investments in high-carbon companies, projects and infrastructures. Hence there is tremendous potential of connecting public support with private finance in an effective and efficient manner [9,22,26,35,106].

This article proposes an adaptive policy design to address specific barriers to low-carbon innovation along the innovation cycle for the technology. Therefore policy makers need to develop the necessary skills such as in-depth knowledge of relevant technological systems, co-ordination skills, patience and flexibility [59,120,170,172,174]. Anticipating future steps in the technology development and commercialization process and having the corresponding policy instruments supports a seamless transition between the stages and gaps. It further enables the redirection of private finance from high-carbon innovation and deployment to clean technologies (see Fig. 5). 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. This requires strong signals from public actors towards research, industry and financiers [35,106,144,182].

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Appendix A

see Appendix Table A.1.

Table A1
Journal landscape describing the financing of low-carbon innovation.

#	Journal	Topics
1	Academy of Management Journal	Venture capital and cleantech industry emergence
1	Administrative Science Quarterly	Stakeholders, environmental movements and industry emergence
2	American Economic Review	Economics of climate change, clean vs. dirty R & D
2	Business Strategy and the Environment	Venture capital, niche-regime-dynamics
2	California Management Review	Cleantech innovation, policy measures
1	Climate Policy	Low-carbon transition, adaptive finance, divestment
10	Ecological Economics	Technical change and regulation, divestment, stranded assets, banking and monetary policies
11	Energy Economics	Energy innovation, energy paradox, climate change and policy, policy risk, diffusion of renewable energy, financial markets
50	Energy policy	Specific clean technologies, renewable energy, policies (market based, feed-in tariffs), renewable energy investment and financing, barriers to renewable energy, innovation systems for clean energy, commercialization and demonstration, regulatory risks, infrastructure, acceptance
2	Energy Research & Social Science	Venture capital and cleantech, future of high-carbon sectors
1	Entrepreneurship, Theory and Practice	New early stage financing mechanisms
3	Environmental Innovation and Societal Transitions	Low-carbon transition, innovation systems, eco-innovation
3	Environmental and Resource Economics	Technological change and regulation, renewable energy finance
4	Industrial and Corporate Change	Industry dynamics and finance, innovation policy, state investments, finance-innovation value chain
6	Industry and Innovation	Innovation systems, regulation, eco-innovation, innovation policy, market creation
1	Innovation and Development,	Innovation systems for sustainability
1	International Review of Financial Analysis	Drivers and barriers for cleantech venture capital
3	Journal of Business Venturing	Entrepreneurial finance, niche-regime dynamics, green entrepreneurship
9	Journal of Cleaner Production	Low-carbon innovation, barriers to cleantech, policies, innovation and diffusion, cleantech venture capital, business models

(continued on next page)

Table A1 *(continued)*

#	Journal	Topics
1	Journal of Environmental Economics and Management	Environmental and technology policy
1	Journal of Law, Economics, and Organization	Regulatory uncertainty and renewable energy investment
1	Journal of Public Economics	Capital market development in Europe
1	Journal of Sustainable Finance and Investment	Technological innovation and divestment
1	Journal of Technology Transfer	Finance-innovation-chain
1	Management Research Review	Eco-innovation and regulation
6	Nature, Nature Climate Change	Low-carbon investment, divestment, value at risk, carbon bubble
2	Organization & Environment	Financing the sustainability transition, venture capital
7	Renewable and Sustainable Energy Reviews	Acceptance of technologies, barriers to renewable energy technologies, policies, investment
18	Research policy	Innovation policy, environmental policy, barriers to low-carbon innovation, sustainability transition, commercialization, policy mixes
1	Resource and Energy Economics	Barriers to energy efficiency, energy paradox
12	Technological Forecasting and Social Change	Technological innovation systems, policies for and barriers to green innovation, modelling, sustainability transitions, stranded assets
1	Technology Analysis & Strategic Management	Cleantech SME and access to finance
1	Technovation	System failures, innovation system for cleantech
1	The Journal of Business	Government venture capital
5	Venture Capital	Entrepreneurial finance, especially venture capital and crowdfunding

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