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Research article

How to finance the transition to low-carbon energy in Europe?

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ABSTRACT

In this paper, we use standard scenarios focussing on renewable energy, energy efficiency and grid investments. We take stock of the literature and quantitative data on available sources of financing for clean energy to qualitatively match supply and demand of specific sources of finance in the European context. Our analysis shows that under the current investment mandates and lending criteria the required funds for a successful energy transition are available. In fact, the current landscape of financing sources can provide between two and six times what is necessary. However, institutional investors and lenders such as pension funds and banks in particular are reluctant to invest in the renewable energy or grid infrastructure because of expected (policy) discontinuities. In addition, more venture capital and household investment are needed to finance low-risk small-ticket projects in the early stages of innovative clean energy technologies, to complement the abundantly available funds for large-scale investments. Based on our analysis, we develop a matrix indicating the role and availability of different sources of finance and new intermediation channels in the energy transition and how these should be deployed.

1. Introduction

Achieving the objectives of the Paris agreement by 2015 will require a significant reduction in greenhouse gas (GHG) emissions and, in particular, CO2 (Rockström et al., 2017). Scholars have proposed technically feasible transition scenarios (see Zappa et al. (2019) for an overview) and the new European Commission has committed to climate neutrality by 2050 (European Commission, 2020). Hence, the transition seems technically feasible and politically urgent. But is this transition also economically feasible and can the required resources be mobilized in time?

Numerous scenarios and models analyse possible pathways towards climate neutrality, with prominent studies coming from IEA/IRENA (WEM) (IEA, 2016; OECD/IEA and IRENA, 2017),[1] PRIMES (Capros et al., 2018; European Commission, 2016)[2] and LIMITS/CD-Links integrated assessment models (IAMs).[3] These studies all highlight the large amounts of investment that are required to make the transition a reality. Such investment is necessary in both established mature technologies as well as innovative technologies (Eyraud et al., 2013; Mathews et al., 2010; McCollum et al., 2018; Polzin, 2017; Polzin et al., 2017; World Economic Forum, 2013). Yet without an adequate supply of financial resources for investment, the technically feasible scenarios may prove unreachable. The challenge for policy makers engineering the transition can thus be summarized under the header of 'moving the trillions' (Sirkis et al., 2015). Rough global estimates for the total investment needs – including infrastructure (Hall et al., 2015; New Climate Economy, 2016) – range from 53 USDtn to 90 USDtn until 2050. Scholars furthermore document model and scenario-based (McCollum et al., 2018, 2013) as well as empirical evidence (Blyth et al., 2015; Jacobsson and Jacobsson, 2012; Peake and Ekins, 2017) to quantify the financing gap for the power sector and the energy transition more broadly. And policy makers respond. Recently, for example, the COP26 private climate agenda was launched by the Bank of England to help the private financial sector address this financing challenge (Bank of England, 2020).

We contribute to this literature and societal discussion by zooming in on the required and available *mix* over the sources of finance (Blyth et al., 2015; Mazzucato and Semieniuk, 2018; Polzin et al., 2018a). McCollum et al. (2013, p. 3) already asserted that '*what this mix of investments should look like is very much an open question*'. But also in the authors' follow-up study in 2018 this question remains largely unaddressed (McCollum et al., 2018). Others have taken up this challenge. Mazzucato and Semieniuk (2018) carefully analysed close to 30.000

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[1] http://www.iea.org/weo/weomodel/.

[2] https://ec.europa.eu/energy/en/data-analysis/energy-modelling.

[3] http://www.feem-project.net/limits/and http://www.cd-links.org/.

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investment deals in the Bloomberg dataset (BNEF, 2014) between 2004 and 2014 and reported that 35% of all investment had some form of public sector involvement. In a much coarser classification, IRENA (2018) reports some 90% of RE projects were being financed privately in 2016. For projections into the future, private investment is likely to take a larger share as risks fall and technologies mature (Mazzucato and Semieniuk, 2018). In this paper we build on their work and ask: *How much private finance is (roughly) needed for a low-carbon energy transition in Europe until 2050.* But more importantly, we add: *In what mix should those resources be(come) available?*

To answer these questions, we first systematically summarize recent model and empirical evidence on the available transition paths and the corresponding investment demands for Europe. We then show that Europe has no aggregate 'financing gap' but faces a qualitative mismatch. We find a lack of private, small-scale equity investment to promote research, development and demonstration (RD&D) for novel technologies, such as energy storage. We also report a lack of low risk but small ticket financing for investments in energy efficiency and decentralized renewable energy projects. Moreover, the abundantly available funds for large scale, institutional investments could be channelled towards grid investments, as this fits institutional investors' mandates. New forms of intermediation and a set of enabling reforms (mainly addressing regulatory issues and standards) could help unlock further under-utilized resources, 'move (some of) the trillions' to where they are most needed and facilitate the energy transition in Europe.

The remainder of this paper is structured as follows: Section 2 positions our work in the literature. Section 3 describes the methodology used to review empirical and model-based evidence as well as literature where section 4 reviews the availability and suitability of different sources of finance. Section 5 discusses our major findings and develops an extended matrix that includes different roles for private investors in the energy transition whereas section 6 derives specific implications for policy makers and financiers.

2. The dynamics of financing low-carbon energy

An innovation-led sustainability transition requires investments in invention and innovation as well as diffusion (Mazzucato et al., 2018; Polzin, 2017; Tian, 2018). In the literature researchers typically ignore the importance of the changing nature of financing needs over the life cycle of projects and technologies (e.g. Blyth et al., 2015) or simply aggregate the funding gap over all sources (e.g. OECD/IEA and IRENA, 2017; World Economic Forum, 2013). This is not problematic if one can assume a sector or technology is more or less in a steady state, implying the relative mix of activities and therefore financing mix is more or less stable. For sectors and economies in transition, however, this may be too restrictive (Geddes and Schmidt, 2020). One could then consider taking a life cycle and entrepreneurial finance approach, in which an innovation-led sustainability transition requires small equity investments in invention and innovation, whereas large scale debt instruments finance diffusion (Mazzucato et al., 2018; Polzin et al., 2017).

The framework developed by Polzin et al. (2017) provides some direction from both the company and technology perspectives to relate the technology life cycle to the required financing mix (see Fig. 1). In the beginning of the technology lifecycle it assumes public R&D investments, grants, prizes and R&D subsidies lead to a positive cash flow for the company developing a new technology. The demonstration, pre-commercial and niche-market phase are the most problematic as cash-flows typically turn negative. Only when reaching the fully commercial phase is the company expected to be profitable and, more importantly, bankable.

From the financing perspective, the framework proposes to distinguish clearly between early stages in the technology lifecycle (innovation/upstream) and later stages (diffusion/deployment/downstream). Fig. 1 shows that different sources of finance are optimal in different stages of the life cycle as projects have different risk/return profiles and these need to match different investors' expectations, sentiments and decision making (see Hamilton and Zindler, 2016 Table 1 for an overview). Correspondingly, private and public actors would need to make the required resources available at the right time and in the suitable

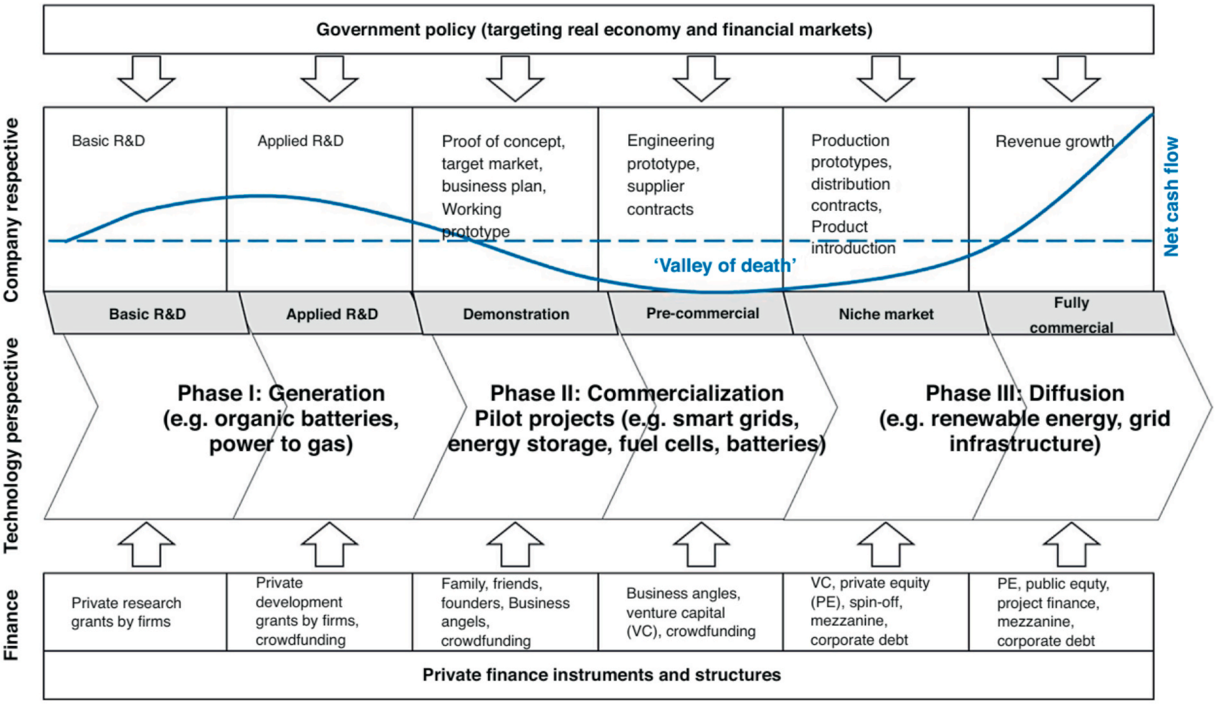

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Fig. 1. Financing energy technology innovation and entrepreneurship (Source: Polzin et al. (2017)).

Table 1
Calculations of sources of finance (Europe).

Source	Calculation lower bound	Calculation upper bound	Source(s)
RD&D finance	Low-carbon energy sources RD&D (average 2014–2017)	RD&D energy budgets (average 2014–2017)	IEA (2019)
Small- and distributed finance	Investment on crowdfunding platforms related to sustainable energy (average 2012–2018)	Financial crowdfunding (new investment 2016)*	Nigam et al. (2018) Ziegler et al. (2018)
VC and private equity	Energy and environment VC/PE investments (average 2007–2015)	High-tech VC/PE investments (average 2007–2015)* All VC/PE investments (average 2007–2015)*	InvestEurope (2017)
Bank finance (debt)	Corporate debt deals clean energy (average 2002–2011)	Volumes of new euro-denominated loans to euro area non-financial corporations (EUR billions; new business)*	BNEF (2013) ECB (2019)
Sovereign wealth funds	Institutional investments in clean energy (average 2007–2013)	Growth Total assets under management in Europe 2017–2018*	OECD (2015a) Preqin (2018, 2017)
Pension funds		Growth total assets under management in Europe (alternative asset class) managed by pension funds (2016–2017)*	EFAMA (2018, 2017)
Insurers		Growth total assets under management in Europe (alternative asset class) managed by pension funds (2016–2017)*	EFAMA (2018, 2017)
State investment banks	Investments in Renewable Energy Projects (average 2004–2014)	Annual investments in 2016 by the 5 biggest State investment banks in Europe*	Mazzucato and Semieniuk, 2018 Mazzucato and Macfarlane (2018)
Green/climate bonds	Fully aligned issuers, climate bonds (2018)	Growth total assets under management in Europe (bond asset class) (2016–2017)*	Climate Bonds Initiative (2018) EFAMA (2018, 2017)
Public equity	Public Equity investments (Average, 2016–2017)	Growth Market Capitalization European Securities (average 2014–2018)*	BNEF (2018) FESE (2019)

Note: * weighted by Industry share of total GDP for new investments (25,1%) taken from https://stats.oecd.org/index.aspx?queryid=60702; Exchange rate for transforming EUR into USD is 1.067 (2015 average taken from https://www.irs.gov/individuals/international-taxpayers/yearly-average-currency-exchange-rates).

form if the transition is to happen. In the literature researchers to date typically ignore the importance of the (changing) nature of financing needs over the life cycle and simply aggregate the funding gap over all sources. Model-based simulations of energy transition pathways give a considerable level of detail on the required levels of investment in different technologies and sectors, so the stylized technology lifecycle can easily be incorporated. Investment demand over the transition can then usefully be split over the most suitable sources of finance.

3. Methodology

To address our research question we build on the methodology deployed by Blyth et al. (2015) referred to as 'systematic narrative synthesis' (Popay et al., 2011). First, we collect 'narratives' about European energy investment needs, using historical data and existing scenarios for future investments, focussing on the power supply system, transmission and distribution as well as energy efficiency. These present the major building blocks for the energy transition more broadly. Because our contribution is not in presenting new energy transition scenarios, we focus here on some widely used and cited models generating energy sector scenarios and projections. Importantly, these scenarios produce quantified investment paths for different energy technologies (see Figs. A1-A.3 in the appendix for an overview and Table A1 for a brief description of the models reviewed).

The method developed in this paper can be applied to any such scenario predictions and models. For illustrative purposes and following the literature in this field, we limit ourselves here to IEA WEM (IEA, 2015; OECD/IEA and IRENA, 2017), and output of the LIMITS (McCollum et al., 2013; Tavoni et al., 2015) and CD-Links projects (McCollum et al., 2018). To reduce complexity, we focus on 6 models and 3 scenarios that predict power sector investments and investment in energy demand reductions (energy efficiency) until 2050. The transformational 2 °C and 1.5 °C scenarios produced by these models assume a full decarbonization of the power sector by 2050 and in that respect do not differ from other IAMs used in the recent reports by the IPCC (IPCC, 2019). We collected key data such as quantified investment needs and cumulative built capacity from these scenarios.

Finally, we roughly estimated the sources of finance available for investments into the energy transition. To have a reasonable estimation on how much financial capacity is available for low-carbon energy development and diffusion, we propose two metrics as upper and lower bounds: Historical average annual investments in sustainable energy technologies arguably constitute a lower bound for the sources of finance (assuming a continuation of at least these levels of commitment is feasible). As upper bound for the different sources of finance we propose the average new investments or yearly growth in assets under management respectively, weighted by share of the industry sector in total GDP to account for the fact that only a fraction of these new funds are available for energy-related investments (see Table 1 for details and sources). This upper bound approximates all new available funds from a given source that could theoretically be directed towards a transformation of the power sector, energy efficiency and grid infrastructure.

We compute these lower and upper bounds for the ten, arguably most relevant, sources of finance for the energy transition over the life cycle of technologies, ranging from early stage RD&D finance, small- and distributed finance and venture capital (VC) in the earliest stages, to pension funds, insurers and traded debt instruments in mature technologies.

4. Sources of finance for the low-carbon energy transition

Few studies and organisations comprehensively assess (potential) sources of finance for the low-carbon energy transition, although their importance is widely acknowledged (e.g. Creutzig et al., 2014; Mazzucato and Semieniuk, 2018; OECD/IEA and IRENA, 2017; Polzin, 2017). Notable exceptions are Bloomberg New Energy Finance (Trends in RE investments 2009–2018) and a report by the Climate Policy Initiative and IRENA (2018), who conclude that the absence of an aggregate financing gap is no guarantee for a successful transition. In this section we summarize the available sources of finance for the energy transition. A systematic summary of the numbers cited in the following sections can be found in Tables A2 and A3 in the appendix.

4.1. *Corporate and government RD&D finance*

In most model simulations the energy sector is assumed to improve its cost-effectiveness while introducing new, renewable and emission free technological solutions over time. For this process to happen, however, technological learning is necessary (Egli et al., 2018; Polzin, 2017; Schilling and Esmundo, 2009). Prior research estimated learning curves in various technological development and diffusion processes (Nemet, 2012, 2006; Pan and Köhler, 2007; Verdolini et al., 2018). Countries around the world are pursuing different strategies to address energy innovation (Chan et al., 2017) but it is well established that R&D investments drive or speed up this learning process (Hannon and Skea, 2014; Olmos et al., 2012; Polzin, 2017). This assumption is also made in the IAMs scenarios for future energy investments as these investments reduce technology costs of the options available (McCollum et al., 2018, 2013). Currently 0.37–1.45 USDbn are made available for RD&D into (low-carbon) energy technologies. This amount falls short of the estimated 14 USDbn annually projected for energy supply and demand RD&D that is required for energy transition in the WITCH model. In addition, both the REMIND and MESSAGE projections to reach the 2 °C or 1.5 °C pathways project high investments in storage technology which is still under development (Beuse et al., 2018).

In principle, the funding for RD&D can come from two sources: public R&D investments and demonstration projects as well as private R&D investments and demonstration. Hannon and Skea (2014) argue that private entities invest sub-optimally in clean energy R&D. Public grants or procurement contracts should finance most pre-deployment activities (Gallagher et al., 2012; Hannon and Skea, 2014; Wilson et al., 2012).

Support for public investments in basic research assumes that new knowledge generated by research organisations trickles down to market participants (Haley and Schuler, 2011). The knowledge generated in basic research, however, is too far from commercialisation to have a direct impact on investors' decision to (not) engage in clean energy production (Polzin et al., 2018a). Moreover, in achieving the 2050 ambitions, some have argued that the focus should be on scaling existing solutions (Hu et al., 2018; Mathews et al., 2010; Parker, 2019). Still, scaling will require learning that can be facilitated with (public) RD&D in the diffusion stage (Pan and Köhler, 2007). Moreover, Haley and Schuler (2011) highlight the positive experience with the Small Business Innovation Research Program (SBIR) and Olmos et al. (2012) assess a broader set of publicly funded instruments such as public loans, equity investments, prizes and tax credits or rebates to support clean energy innovation processes. Public loans to small firms and start-ups may not be appropriate because of their limited ability to pay them back and tax credits prove to be unfruitful given the low profits of small innovating firms. Instead, public equity investments can provide a solution. Such investments give the public sector an upside and could signal quality to private investors (Howell, 2017; Islam et al., 2018). If the expected revenues of an innovation are deeply negative, prizes or input-driven subsidies (grants or contracts) would be a suitable public funding option (Olmos et al., 2012).

4.2. Small- and distributed finance

Small scale financial sources increase diversity in financial systems which is simultaneously beneficial for energy investments and the stability of the financial system (Polzin et al., 2017). Small- and distributed finance (especially crowdfunding and crowdinvesting) can play a significant role in funding investments in a more decentralized energy system. Equity and debt crowdfunding have experienced rapid growth in the last 4–5 years, mainly due to technological advancement and regulatory innovation. Still, the volumes are relatively small: up to 2 USDbn might be available for investment in the energy transition in Europe. Peer-to-business lending, equity- and reward-based crowdfunding as well as real estate crowdfunding have the most relevance for investments in renewable energy – both upstream (for innovative start-ups) and downstream (citizens and cooperative RE projects) (Vasileiadou et al., 2015). For example, Windcentrale, the largest crowdfunding initiative in the Netherlands, attracted more than 15 USDmn in equity investments (Vasileiadou et al., 2015). In the past the lending-based model has contributed even more to financing sustainable energy projects (Nigam et al., 2018).

Most models predict, for the most ambitious scenarios, a large role for decentralized energy efficiency improvements such as home insulation or lighting (e.g. Capros et al., 2018; Jenkins and Hopkins, 2019; OECD/IEA and IRENA, 2017; Schanes et al., 2018). In the IAE/WEM projections, this investment category surpasses all other projections (136 USDbn annually vs. 32 USDbn in the 2 °C scenario in the most ambitious model WITCH) (see appendix A.1). Due to the small ticket size, however, these investments are currently not attractive for banks or institutional investors. Small and distributed finance of both equity and debt type, is very suitable to finance these types of investments. Also these models mobilize resources from heterogeneous groups, ranging from financial investors to non-traditional small-scale investors such as farmers and wealthy individuals (Vasileiadou et al., 2015). Engaging citizens in this way reduces perceived risks of RE and has the potential to democratize the energy transition. However, for small- and distributed finance to work, scholars agree that policy instruments such as feed-in tariffs, quota-based subsidy schemes, tax incentives or grants are critical (Curtin et al., 2017).

4.3. Venture capital and private equity

Venture capitalists (VCs) provide entrepreneurs with funding between the R&D phase and commercialisation (Marcus et al., 2013). Venture capital funds are regularly structured as 10-year partnerships, where outside investors (the limited partners) provide capital to the VC fund (run by the general partners) to make high-risk, high-reward investments, typically consisting of a portfolio of 10–20 start-ups (Gaddy et al., 2017). They can hence play a critical role in bridging the 'valley of death' that new companies face when their technology is too advanced to receive public research support but not yet technically or commercially mature (Migendt et al., 2017). We estimate the potential contributions of VC and PE to the energy transition to be between 2.58 and 4.61 USDbn annually.

These resources flow increasingly to energy efficiency, software, energy-storage and transportation characterised by high technology risk, high potential scalability and low capital intensity (Gaddy et al., 2017; Ghosh and Nanda, 2010). Other technologies, that feature prominently in the scenarios, such as offshore wind farms, advanced biofuel refineries or the first commercial plants for unproven solar cell technologies, are less attractive for VC investment. This is due to high capital expenditure (CAPEX), significant policy risk, and the fact that these technologies compete in the merit-order with the (low) variable cost of continuing operation of existing plants (Tian, 2018).

To better judge the potential of VC investments, three interdependent characteristics of markets—growth, scalability, and rapid payoffs—are important (Kenney and Hargadon, 2012). Many technologies such as grid infrastructure, solar facility installations or biofuels therefore do not feature the growth, scalability, and rapid payoffs that are important to the VC business model (Kenney and Hargadon, 2012). Investors would need to accept more investment and involvement in firms at earlier and later stages and essentially 'move out of their comfort zone' (Marcus et al., 2013). The interdependence of the infrastructure and clean technologies (e.g. electric vehicles and charging stations) also adds policy risk to investments that VC-investors and their investees cannot manage. VC investors will make many small investments in a large number of less mature companies to hedge against business risks (Marcus et al., 2013) but will simply stay away from political risk (e.g. Sanders et al., 2013).

To address barriers to successful VC engagement in clean energy, scholars analysed a menu of policy options. Both supply side policies (university R&D support, SBIR grants) and deployment policies (feed-in tariffs, regulations and standards) designed with a long-term perspective of creating a market for environmental technologies, are associated with higher levels of venture capital (Criscuolo and Menon, 2015; Polzin et al., 2018a). Certain (de)regulatory actions, large-scale demonstration projects, and/or procurement decisions can encourage entrepreneurial activity and corresponding VC investments by building the essential knowledge- and social networks (Kenney and Hargadon, 2012). Policy makers may also change the framework conditions for early-stage VC/PE investments in general. Increasing the functioning of equity capital markets will allow investors to sell the companies they have grown through a trade sale or initial public offering (IPO). Other framework conditions include most notably the tax regime that encourages risky early-stage investments and allows for strong incentives in managerial contracts (Elert et al., 2019). An entrepreneur-friendly bankruptcy legislation and exit possibilities would also encourage more potential entrepreneurs to enter the uncertain clean energy sector (Polzin et al., 2018b, 2018a).

4.4. *Bank finance (debt)*

Banks are one of the major sources of finance both for SMEs/companies (corporate debt on-balance sheet financing) as well as project finance (Steffen, 2018). From 2002 to 2012 corporate lending to companies operating in the clean energy sphere in Europe averaged at around 3 USDbn with a potential of more than 38 USDbn. Zindler and Locklin (2016) assert that to date, the vast majority of debt for clean energy power generation has been financed through direct loans from project financiers, such as major banks. Hence, we see a strong need and potential for engaging banks in the financing of renewable energy technologies. The predicted amounts in the model simulations range from 51 USDbn (IMAGE model) to more than 120 USDbn annually (REMIND model) in the 2°C scenarios. Scholars also point out banks suitability in financing energy efficiency applications such as retrofitting homes and office spaces with more energy efficient materials, since these projects are closely related to real estate finance and do not face technology or market risks (Ghosh and Nanda, 2010). The problem here is that the tickets are very small as such investments are made on a project by project and building by building basis.

There are two main barriers relating to the large-scale deployment of bank finance for clean energy. First, after the global financial crisis banks saw a period of lack of confidence and decreased economic activity combined with increased regulation and compliance. This led to lower overall levels of lending (Campiglio, 2016; Polzin et al., 2017). In addition, unintended consequences of the regulatory backlash, such as the Basel III financial regulations, constrain banks to finance long-term infrastructure projects (Ang et al., 2017; Röttgers et al., 2018). Campiglio (2016) discusses the relevance and feasibility of using macro-prudential financial regulation to expand the amount of credit flowing to low-carbon activities by assigning higher risk weights to ‘brown’ vs. ‘green loans’ (Thomä and Gibhardt, 2019), relaxing liquidity rules and matching long-term loans with similarly long-term liabilities.

The second factor limiting green investments is their unattractive risk/return profile. Many banks are constrained in their ability or interest in extending long-term loans due to the relatively short maturity on the liability side of their balance sheets. However, many clean energy projects (including energy efficient buildings) are long-term in nature. Banks are currently ill-equipped to assess environmental and technology risks. The lack of borrowers' environmental information (e.g., borrowers' emissions data and technologies employed) limits banks' ability to assess the environmental risks involved in project and corporate finance (Campiglio, 2016; G20 Green Finance Study Group, 2016). Most importantly, clean energy investments are perceived as being dependent on public support, which has not been as transparent and predictable as banks would like to see it. In some cases, this has gone so far as to introduce retroactive adjustments to public policy producing strong credibility issues for years to come (Campiglio, 2016). Interestingly, government support for carbon intensive industries has been (deemed) much more reliable in past decades. Financial authorities, however, are increasingly taking initiatives to promote coordinated responses for clean energy finance in the banking sector. They do so in consultation with key stakeholders such as banking associations, banking regulators, relevant ministries, securities exchanges, and credit rating agencies (G20 Green Finance Study Group, 2016). Another practice is exemplified by the US Department of Energy (DOE) ‘Loan Program’ that aimed at scaling up domestic innovative and mature clean energy technologies. Whereas the success cases include Tesla motors, many fast growing companies could not absorb the excess liquidity and failed in the process (Kenney and Hargadon, 2012).

4.5. *Institutional investors (public and private equity, bonds)*

Institutional investors such as sovereign wealth funds, pension funds and insurance companies are among the largest sources of capital in today's financial markets with total assets under management (AUM) of 63 USDtn[4] in the OECD countries alone. Many of the studies exploring the barriers to engagement of institutional investors especially with respect to renewable energy have focused on the problems with government support for infrastructure projects, lack of investor capabilities (principles and skills) and problems with investment conditions (commercial and technical risks as well as market risks related to the projects themselves) (G20 Green Finance Study Group, 2016; IRENA, 2016; Kaminker and Stewart, 2012).

Scholars and industry organisations have thus identified political, policy, regulatory, commercial and technical risks as well as market risks (IRENA, 2016; Kaminker and Stewart, 2012). Longevity risk (i.e. long-term performance) is also perceived to be severe (‘tragedy of the horizons’) as energy systems need to be built around new technologies (such as wind and solar). Commodity price volatility (i.e. future electricity prices) is therefore considered a severe risk (Röttgers et al., 2018). In addition, institutional investors are concerned with the mismatch between the long-term nature of capital commitments inherent in clean energy financing and the relatively short time horizon that is adopted and enforced in their mandates and financial regulation (Kaminker and Stewart, 2012). Finally, as in banking, policy and regulatory changes pose a real threat to clean energy financing.

All of the scenarios for transition feature significant large-scale RE investments (Wind, Solar PV, Hydro and Biomass). Wind energy investment needs range from 19 USDbn to 50 USDbn annually in the 2°C compatible scenarios whereas Solar ranges between 7 and 73 USDbn. All of the IAMs also assume sizable Hydro power investments (7–20 USDbn). The projects in these sectors typically fit the ticket-size/risk profile of institutional investors. Interestingly, model predictions vary dramatically when it comes to the future role of Biomass (0–15 USDbn) (e.g. Rodriguez et al., 2017). But as this technology is not readily scalable and features (uncertain) fuel costs, it is less attractive for institutional investors. Finally, all models in all scenarios predict significant investments in transmission and distribution (networks) that will have to enable the penetration of more intermittent renewables on the grid. These projects too fit the investment mandate of institutional investors.

4.5.1. *Sovereign wealth funds*

Sovereign Wealth Funds (SWF) often combine a long-term investment with socially responsible investment (SRI) objectives, aiming to address significant public policy issues that could affect intergenerational aspects of sustainability (Farrell and Löw Beer, 2019). Examples include the Norwegian SWF fund with AUM of more than 1 USDtn. According to the SWF Institute, green growth investments are increasingly becoming a focus for SWF funds (Kaminker et al., 2013). In Europe, SWFs could provide more than 100 USDbn in investments annually. Given the relatively large ticket size and low-risk profile these funds look

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[4] Q4-2018 AUM Insurance corporations and pension funds (source: OECD).

for, however, this source might be most suited for investments in grid infrastructure (fixed return by the grid operator). Such investments are projected to require between 31 and 80 USDbn annually (2°C compatible scenarios).

4.5.2. *Pension funds*

Pension funds (most operating under a defined contribution scheme) represent one of the major sources of long-term finance for clean energy companies and projects (OECD, 2015a; Röttgers et al., 2018; Della Croce et al., 2011). Pension funds could mobilize investments worth more than 77 USDbn for clean energy every year. In Europe there are fewer large pension funds and smaller total assets in pension funds than in North America. Boermans and Galema (2019) show that actively divesting from fossil fuels has no negative risk-adjusted performance implications in a study on Dutch pension funds. Therefore, shifting more funds towards more sustainable investment opportunities seem feasible without compromising on pension funds main mandate.

The main exposure of institutional investors to clean energy has so far been via shareholdings of the debt and equity of listed utility companies (OECD, 2015a). This funding channel is limited by the willingness of institutional investors to buy new debt and equity issued by utility companies (Kaminker and Stewart, 2012). Other channels include the investment via infrastructure project funds, direct investments into projects or asset-backed securities (special purpose vehicles) or unlisted (direct), intermediated and listed (direct) equity (OECD, 2015a). Examples of the latter include World Bank Green Bonds or the direct investments in SolarReserve by the public pension fund of California (Calpers) (OECD, 2015a). Direct investment, however, is the most difficult type of investment for institutional investors due to the skills and resources required (Nelson and Pierpont, 2013). Some large pension funds active in this field are known to have developed significant in-house expertise but most smaller ones simply outsource the management of their investment portfolio. Research by the Climate Policy Initiative (CPI) suggests that AUM around 50 USDbn are needed in order to justify the costs of building a dedicated team to invest directly in clean energy projects (Nelson and Pierpont, 2013).

In terms of sector/technology allocation, most of these investments are related to technologically mature wind energy. Infrastructure projects can in principle be financed through pension fund money, as these projects are bankable and offer the opportunity for long-term contracts with reliable counter parties, often with inflation protection (Kaminker and Stewart, 2012). The 2°C scenarios reviewed in this paper project 19–50 USDbn worth of investments in wind annually. The exposure of pension funds to clean energy is limited, however, by liquidity and solvency regulations and frequent benchmarking on indices that makes the investments effectively short term (Kaminker and Stewart, 2012).

To overcome these structural barriers to investment, scholars suggest adjusting the prudential regulatory framework towards long term investment. This entails addressing short term risk management, the primary focus on solvency as well as the bias towards pro-cyclicality (Della Croce et al., 2011). Institutional investors should also be allowed to invest into less liquid assets, such as unlisted infrastructure and VC/PE, even if pricing these assets might be problematic. In addition, it is recommended that governments establish the appropriate regulatory, supervisory and tax frameworks for such investors to develop (Della Croce et al., 2011; Elert et al., 2019). These regulatory changes, however, are yet to be implemented.

In parallel, some institutional investors (for example CalPERS) decided to invest in clean technology funds as part of their ethical mandate (Kenney and Hargadon, 2012). It is important to note that green investment has traditionally been embedded in a broader approach of SRI or ESG (environmental, social and governance) (Tian, 2018), opening up a large potential number of projects that fit the pension funds' mandates and preferences.

4.5.3. *Insurance companies*

(Re-)insurance companies constitute a final category of institutional investors that could provide up to an estimated 158 USDbn per year to finance clean energy. The availability of proprietary and internal historical data on the performance of clean energy from their insurance (underwriting) business units may also give some insurers a particular information advantage (Kaminker et al., 2013). Similar to pension funds, insurance companies have to date invested mainly in wind power projects and companies. However, they also invested in venture capital, private equity, public equity and debt that has found its way to cleantech sectors (Kaminker et al., 2013). Going forward, infrastructure finance (31-80 USDbn) and increased commitment to wind (19-50 USDbn) and hydro (7–20 USDbn) would best fit their current mandate and risk appetite.

Major barriers for investing into clean energy, in addition to the general considerations for institutional investors, revolve around specific regulation for insurers and pension funds (Solvency II). These regulations can, unintentionally, exacerbate the focus on short-term performance, especially when assets and liabilities are to be valued at market prices (Della Croce et al., 2011). Various measures that have been implemented, including a dampener on equity risk to prevent insurers from divesting in a crisis period, should help mitigate these potential effects. Still, Solvency II penalises infrastructure and other less liquid long-term assets, which may hamper their engagement in clean energy investments (Della Croce et al., 2011).

4.6. *State investment banks*

A State Investment Bank (SIB) is a public entity established to facilitate private investment into, politically desirable projects (Campiglio, 2016; OECD, 2015b). Most SIBs have programs focussing on promoting investment in renewable energy and energy efficiency (OECD, 2016). Examples include UK's Green Investment Bank and the German KfW (OECD, 2017). Governments have created SIBs with a narrow mandate focussing mainly on mobilising private investment by using interventions to mitigate risks and enable transactions. As an independent authority they usually have a degree of latitude to design and implement interventions and a focus on cost-effectiveness. However, their performance is regularly reported and evaluated by the respective governments (OECD, 2015b).

A recent study by Mazzucato and Macfarlane (2018) found that selected European SIBs could provide up to 60 USDbn in annual financing, leveraging this into a multiple of private investment for clean energy (Geddes et al., 2018). Röttgers et al. (2018) show that in more than 30% of the clean energy projects that are currently financed by institutional investors, SIBs were involved. When looking at the technology mix required in the transformational pathways (2° and 1.5°), SIBs can play a role especially in those that include large energy storage investments and energy efficiency investments.

Mazzucato and Penna (2016) underline that SIBs 'shape and create' markets, rather than provide fixes to market failures. Many SIBs also play a 'mission-oriented' role, making key investments in new sectors. Correspondingly, Mazzucato and Semieniuk (2018) highlight that publicly owned entities invest early on in the technology life cycle and invest significant sums in high-risk renewable energy projects. The authors later extend their findings with a quantitative analysis showing the significant influence of public finance in mobilising private clean energy finance (Deleidi et al., 2020). Next to capital provision and de-risking, SIBs fulfil an educational role (risk assessment and internal expertise), a signalling role (reputation and crowding-in private finance and financing costs), and the role of being a first or early mover (new deal structures, manufacturers and developers) (Geddes et al., 2018). The latter might prove especially valuable when it comes to new storage technologies, such as included in the transformational pathways of the models REMIND and WITCH.

Specific instruments that SIBs can deploy include concessional loans, loan loss reserves, guarantees, insurance and subordinated debt. Transaction enablers such as securitisation, i.e. the bundling of small investments into a larger vehicle, co-investment and on-bill financing (OECD, 2015b) could alleviate financing constraints with regard to small-scale energy efficiency investments that are part of all the 2° or 1.5° scenarios we consider.

4.7. Publicly traded equity

Equity from listed/traded companies (mostly energy utilities) has been one of the major sources of corporate finance for the clean energy companies in the past decade (Criscuolo and Menon, 2015), especially for mature RE technologies and energy efficiency. Institutional investors such as pension funds and insurance companies have invested in such stock as it typically gives a reliable dividend (Kaminker et al., 2013). Olmos et al. (2012) also highlight the function of governmental equity investments in innovative companies to win back part of the RD&D support given in earlier stages of the company's lifecycle. Equity markets also play an important role as an exit channel for initial public offerings, motivating VC and private equity investments in cleantech firms (Migendt et al., 2017; Mrkajic et al., 2017).

Cumulative investments, however, have been rather limited in the past (see lower bound of 2.41 USDbn) whereas the potential volume of this source of finance can be as high as 221 USDbn annually). Although listed equity potentially taps into a vast market, it is not yet catalysing clean energy investments, which is mainly related to regulatory and disclosure issues. To allow for a meaningful comparison of green equities and create sensible benchmarks, standardized disclosure agreements need to be developed (G20 Green Finance Study Group, 2016). The listing of green bonds might play a role for public equity markets in the clean energy investment field (G20 Green Finance Study Group, 2016). Another relevant development in this area, especially in the European context, is the process of developing a standardized European Green Taxonomy to support the European Green Deal.

4.8. Intermediate channels

4.8.1. Green/climate bonds

One can also allow institutional investors to make clean energy investments also via the fixed income part of their investment portfolio through the issuance of green bonds (IRENA, 2016; Kaminker et al., 2013; Kaminker and Stewart, 2012). Europe's 509 USDbn climate-aligned bond market is composed of 291 USDbn in bonds issued by fully aligned issuers, 145 USDbn of labelled green bonds and 73 USDbn of bonds issued by strongly aligned issuers (Climate Bonds Initiative, 2018). From estimates based on EFAMA market data this study concludes that more than 191 USDbn annually could potentially be invested by institutional investors through climate bonds. To date, climate bonds have been used to finance mature hydro energy, but increasingly these investments include solar and wind projects (Tian, 2018). These technologies all feature prominently in the scenarios, especially those that rely heavily on RE to achieve a 2° compatible scenario such as POLES, REMIND and WITCH. With investment in wind ranging from 19 to 50 USDbn, solar PV 7-73 USDbn, and in hydro from 7 to 20 USDbn annually, there is significant room to develop a mature and deep green bond market in Europe.

Green bond definitions and requirements for disclosure, however, are the basis for developing a credible green bond market and for avoiding 'green washing' (G20 Green Finance Study Group, 2016). Globally, the most widely accepted sets of principles are the Green Bond Principles and the Climate Bonds Initiative's standards. Barriers to the further expansion of green bonds markets lie in the limited awareness of the benefits of green bonds as well as a lack of standardized green bond ratings, indices and listings. Again, the European initiative to develop a Green Taxonomy can be understood as a project that aims to promote such development. Furthermore, international investors might have difficulties accessing local markets and domestic green investors might not have the capacity to invest in them (G20 Green Finance Study Group, 2016). To develop this route of financing for institutional investors and banks, policy makers would need to revise covered bond regulation allowing banks to issue covered bonds based on clean energy loans and allowing pension funds and insurers to buy them (OECD, 2015a).

4.8.2. YieldCos

Since 2014, the YieldCo structure has emerged as an option for energy utilities and other clean energy asset owners to spin off operating assets from their balance sheets (La Monaca et al., 2018; OECD, 2015a; Tian, 2018). YieldCo's are listed intermediaries between investors and infrastructure projects that also rely on public markets. A YieldCo collects the stable cash flows and distributes them through public markets to shareholders as dividends while providing liquidity by allowing investors to easily buy and sell shares. YieldCos can enable institutional investors to invest equity directly in corporations and take an ownership share in operational clean energy assets. Institutional investors can thus access a portfolio of renewable energy projects through YieldCos as a new type of investment target with lower risks, especially construction risk (OECD, 2015a), while these vehicles allow the developers to offload the risk and move on to the next project. YieldCos can also issue green bonds and potentially provide a major share of future equity investments into clean energy (OECD, 2015a; Zindler and Locklin, 2016).

The success of YieldCos largely depends on growth and the ability to acquire new assets that can deliver steady cash flows. A recent study found that the YieldCo concept can thus provide an advantage by reducing the capital costs of renewable energy projects while providing low-risk returns to investors, thereby mitigating the social cost of achieving clean energypolicy objectives (La Monaca et al., 2018).

4.9. Summary

In the above we have discussed the various sources of investable financial resources for the energy transition, focusing on the power sector, energy efficiency and grid infrastructure investments. We collected and estimated ranges for all these sources and confront these with the demand as projected in the scenario studies (see Appendix A.3). It should be recognized that the fit between sources of funding on one hand and technologies and investments to be funded on the other, is not perfectly aligned. In the end, the financial structuring of individual projects depends on so many idiosyncratic factors, that such a matching is impossible to make.

In Fig. 2 we synthesize the findings from our literature review regarding potential sources of finance for the different technologies required for a successful energy transition. If we compare the available sources of funding (upper bound) per technology with the required funds to realize the average demand in transition scenarios that will prevent catastrophic climate change we see that (more than) sufficient funds are available (up to almost 6 times the volume for solar PV for example). When looking at the lower bound supply, one should take the large quantities of green/climate bonds that might be available with a grain of salt as there are no transparent standards and options for verifying that investments are in fact 'green' (i.e. going to energy efficiency or renewable energy).

5. Discussion

The question guiding our inquiry was: *How much private finance is (roughly) needed for a low-carbon energy transition in Europe until 2050 and in what mix should it be(come) available?* Building on empirical evidence and modelling work in the literature, this paper set out to compare investment needs to available sources of finance for the energy transition in Europe and, more importantly, systematically explore where the money can come from and what kind of financiers need to be engaged

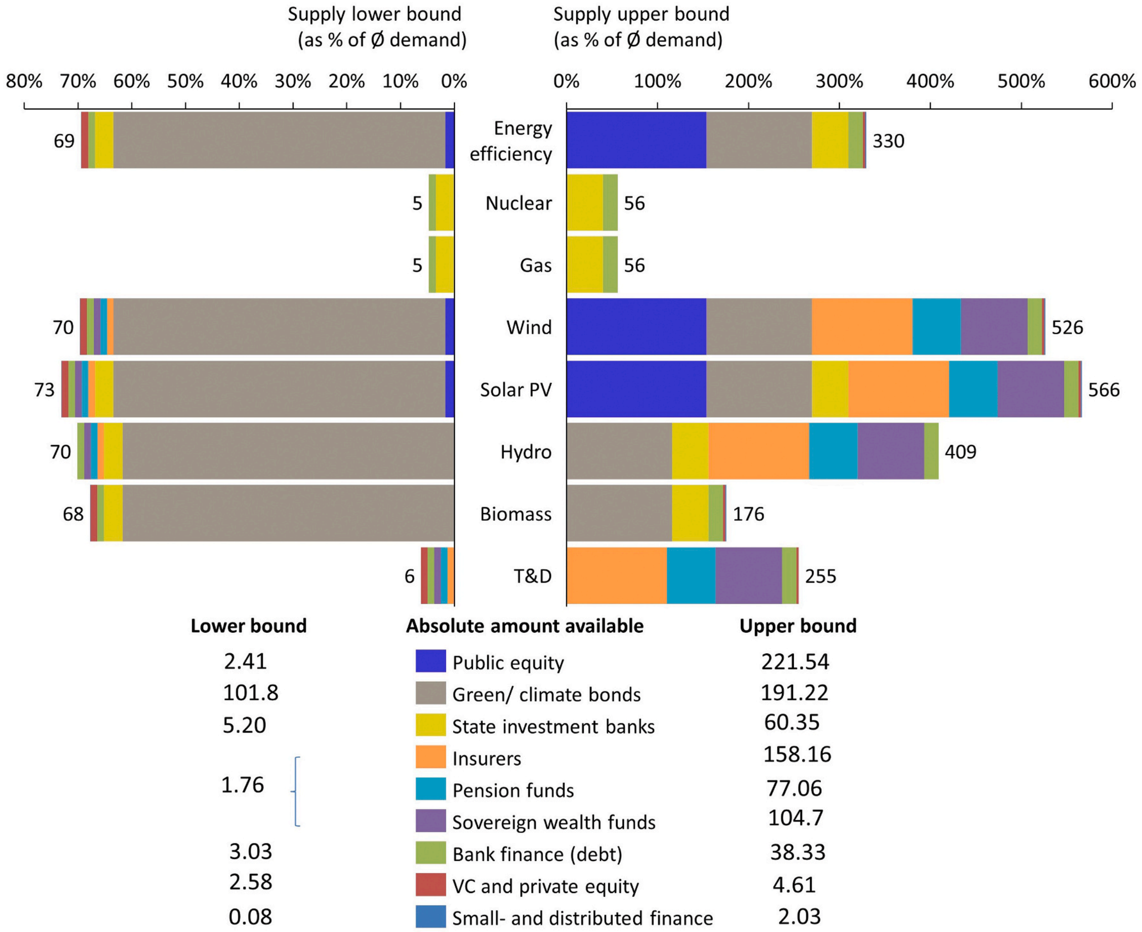

Fig. 2. Contrasting finance demand and supply per source and technology (Note: The share of a particular sources of finance is calculated by dividing the supply (lower bound/upper bound) by the aggregated demand of technologies which fit this source; Numbers underlying this Figure can be found in Appendix A.3).

(more) in order to allow for an innovation-led energy transition. Our analysis shows that overall, the financial resources are available in the order of magnitude that is needed for a successful energy transition, especially when it comes to institutional investors.

Fig. 3 depicts the average supply of different sources of finance for the energy transition and links them to investment characteristics (see Table A3). The *blue colour* represents the sweet spot for institutional investors that includes wind farms, utility scale solar PV and first-generation biofuel refineries as well as transmission and distribution infrastructure. Investments in this quadrant come in big tickets and have low operational, market and regulatory risks. These projects also feature a stable cash flow and low risk profile. In this category we also find component manufacturers for wind and solar or energy efficiency services. As can be seen from the Figure these are by far the largest sources of finance.

Even within the current composition of equities, bonds and alternative investments, institutional investors could engage in financing large-scale (low-risk) renewable energy projects and grid infrastructure (OECD, 2015a; Röttgers et al., 2018; Zindler and Locklin, 2016). An effective reform of regulation and governance that enables and incentivises institutional investors to engage more in unlisted long-term equity and (green) debt would make ample funding available to scale the technologies that can carry the energy transition. Finally, these investments could be realised through intermediate channels such as green bonds or YieldCos and institutional investors could be allowed (Gevorkyan et al., 2016; Kaminker et al., 2013; Kaminker and Stewart, 2012; Tian, 2018) and incentivized to engage more in public equity markets (La Monaca et al., 2018; Zindler and Locklin, 2016).

The *grey colour* exhibits finance for innovative technologies such as fuel cells, power storage or electric drive trains that are at a small-scale demonstration level and carry significant technical and market risk. Here we should also look for the technological innovations that can help fit intermittent and low intensity renewables to our grids. Next to venture capital that focuses on rapidly scalable solutions, small- and distributed finance emerged to service this niche alongside continued (public) RD&D support.

However, in the earlier stages of the technology lifecycle the financing gap seems more urgent, especially when it comes to highly risky investments. There we see possible shortages in innovation finance, especially RD&D and venture capital and private equity. Here the required amounts are smaller, but the downstream impacts of shortages are not. If we starve the early stage development and diffusion of knowledge, we endanger the realization of learning effects that are fundamental in keeping the costs of the energy transition manageable. Small- and distributed finance and venture capital are available to complement traditional public R&D funds, where only the former are also able to address the significant policy risks in the renewable energy sector (Polzin et al., 2017). Moreover, especially in to address the challenges of fitting increasing shares of intermittent renewable energy on the respective grids (i.e. through advanced storage solutions) and solving issues in niche markets, financing small scale, experimental venturing will be important qualitatively if not quantitatively in driving the energy transition.

There is no quantitative issue in freeing up (public and private)

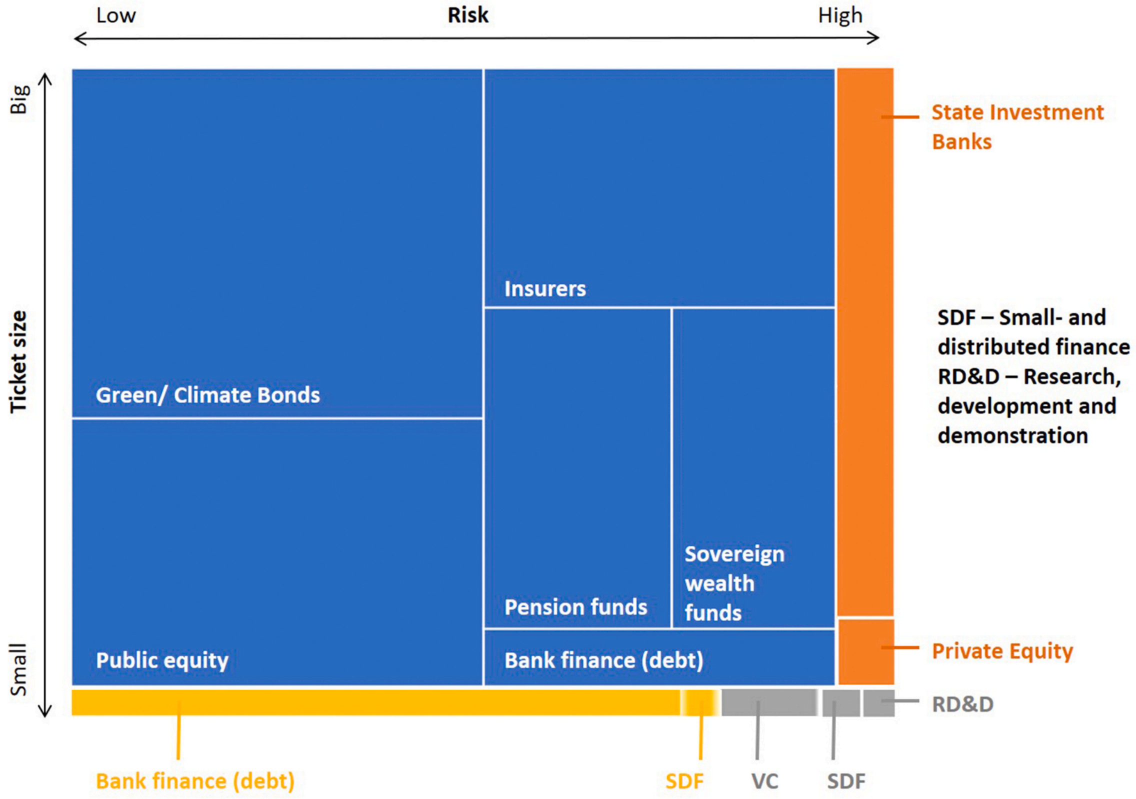

Fig. 3. Availability of sources of finance for the energy transition (framework adapted from Criscuolo and Menon (2015); Note: the relative size of the rectangles represents the average availability per sources of finance, the numbers underlying this Figure can be found in Table A.3).

resources and a little will go a long way in solving the most urgent bottlenecks. However typically the types of finance suitable for funding these type of projects are not so easy to mobilize in Europe's highly institutionalized, bank based and tightly regulated financial sector (Bertoni et al., 2015; Elert et al., 2019; Polzin et al., 2017). Large ticket sizes with higher risks can be handled effectively by (state) investment banks and some private equity funds. State investment banks have the potential to scale-up their investments significantly; however, their main role would be in mobilising private finance through co-investments, signalling and education (Geddes et al., 2018). More important is the development of alternative mechanisms to handle small tickets with high risk. In this the SIBs can take a role, not so much in providing funds as in organizing the platforms and infrastructures.

The *orange colour* features the 'hard-to-finance' projects and companies combining large scale with a high risk such as offshore wind farms, advanced biofuels and first commercial plants of unproven technologies. To some degree only private equity funds or (state) investment banks can effectively engage in this types of technologies. By contrast in low risk small scale projects (*yellow colour*), mostly in energy efficiency and residential building improvement, both traditional banks and modern platform-based crowdfunding can play a role. In the latter case, innovation in the financial sector itself is an important channel for making policy, and we discuss this quadrant in more detail below.

6. Conclusions and implications

Our analysis for the demand and (potential) supply for clean energy finance in Europe shows that sufficient money is in principle available. However, matching investment demand and supply in a qualitative sense, proves challenging. The resources are sometimes not available in the form they are most needed. We show there is a lack of private small-scale equity investment to promote RD&D and early stage venturing, whereas low risk but small ticket financing of energy efficiency investments would require platform-based intermediation to complement traditional relationship banking. We also note that the large scale, low risk debt investments are not yet free to move into renewable energy projects, energy efficiency and transmission/distribution infrastructure, instead being pushed into existing real estate and more liquid government debt. New forms of intermediation and a set of enabling reforms (mainly addressing regulatory issues and setting standards) could help unlock under-utilized small-scale and large-scale sources and facilitate the energy transition in Europe. Public funding alone cannot finance the energy transition and the private sector needs to engage. We conclude they have the means to do so and would be willing, but well designed and thought-through financial reform, not additional billions from the European Commission, should be at the heart of the European Green Deal and transition strategy.

6.1. Policy implications

Earlier research pointed out that current financial efforts fall short in reaching the Paris agreement pathways for a 2°C world (McCollum et al., 2018; Peake and Ekins, 2017). Our analysis shows that this is not a supply problem. The required financial resources are available in ample supply, even if we take specific constraints and investment preferences into account. As a policy maker, 'moving the trillions' and mobilising private finance for the energy transition can then be approached from two perspectives (e.g. Polzin, 2017; Polzin et al., 2018a, 2017): policies targeting the real economy (the energy sector) and those targeting the different sources of finance.

First, *climate and energy policies* play a crucial role in attracting investors (Gevorkyan et al., 2016; Grubler et al., 2012; Polzin et al., 2019; Wilson et al., 2012). These policies range from putting a price on carbon (Gevorkyan et al., 2016) to instruments such as feed-in tariffs, renewable portfolio standards, product regulations (e.g., stricter appliance, building, and vehicle efficiency standards) or RD&D subsidies (Polzin et al., 2019). Almost all of the investment scenarios reaching a 2°C compatible path, assume a deployment of a portfolio of policies to promote innovation and diffusion of clean energy (European Commission, 2016; McCollum et al., 2018, 2013; OECD/IEA and IRENA, 2017). We emphasise that the policies implemented, should consider the implications for investors of different types. A steady hand and long run reliability of policy programs is essential for their effectiveness, perhaps even more so than the amounts of public money spent. This is especially relevant in the midst of the COVID19 crisis where policies targeting the energy transition might be stopped or cancelled because of the focus on short-term economic relief (Steffen et al., 2020). If governments better understand the realities of investors providing different sources of finance, they can shape the essential energy transition policies in a way that minimizes policy risk, which is a key barrier to investment for all sources of finance. That is, the transition can be cheaper, faster and financially more feasible simply if it is planned and implemented well. However, investors need to understand that when the government takes the risks in the transition it needs to generate revenue as well, for example by selling early equity investments (see section 4.2) or by appropriate taxation. In the long run, gradually 're-risking' established renewable energy technologies by phasing out policy support reduces policy cost (Polzin et al., 2019).

Second, policy makers need to specifically address *regulatory barriers* to clean energy investment. These include adjusted liquidity requirements for institutional investors, benchmarking and key performance indicators, asset risk classification to reflect climate risks for asset managers and banks as well as the prudential regulatory framework valuing long-term investments and lending for the banking sector. This is, politically, not so easy. The rules and regulations this refers to, are there to ensure financial stability. They were not designed with the climate crisis or the energy transition in mind. It will be challenging to redesign regulatory frameworks in such a way that investors can engage, while the other public interests remain safeguarded.

This paper also adds recommendations specific for the major sources of finance. Scholars and practitioners alike recommend a strong role for the government in innovation *(RD&D)* finance, so governments should break the downward trend in that respect. Given the large financing gap of many clean energy innovation projects for new technologies and the inherent need to push known technologies down the learning curve faster, public grants and contracts should finance a significant part of them (Hannon and Skea, 2014; Mazzucato and Semieniuk, 2018, 2017). Especially in countries where interest on government bonds is low, it makes perfect sense to borrow cheap to finance risky, but in the aggregate highly profitable investments in knowledge and basic research. Moreover, it makes sense to launch these programs in those countries that have a strong knowledge infrastructure. Other instruments to promote innovation and learning include public loans, equity investments, prizes and tax credits or rebates that can efficiently support the innovation and learning processes (Olmos et al., 2012).

For *small-scale finance*, such as crowdfunding, policy makers need to strike a balance between protecting individual investors and developing new forms of cooperative finance (energy cooperatives) that attract these investors. For example, standardising cooperative investment contracts would reduce transaction costs and enable a scaling up of decentralized energy efficiency investments – also as a measure of economic recovery after COVID19 (Hepburn et al., 2020). Additionally, governments could take a role in building up and securing the infrastructures for small direct finance, such as equity and lending crowd funding platforms. Finally, forcing less savings into pension funds would free up these resources for long-term investment and/or experimentation through small-scale finance (e.g. Elert et al., 2019).

Engaging risk finance *(VC/PE)* requires an adjustment on the level of the European financial ecosystem i.e. increasing the availability of local (institutional) anchor investors as well as the exit opportunities through strengthening European public equity markets. Their returns in many energy transition projects depend on complementary large-scale infrastructure investments. This is an example of the interdependencies between small- and large-scale and low- and high-risk finance in the energy transition. Furthermore, a reform in tax regime for early stage investments and entrepreneur-friendly bankruptcy legislation would encourage VC investment across the board, also for the energy transition (Elert et al., 2019). In addition, SBIR grants, university R&D support, (de)regulatory actions in the energy sector, large-scale demonstration projects, and/or procurement decisions would also be beneficial for the early stages of technology deployment that VC investors target (Kenney and Hargadon, 2014, 2012).

Banks suffer from a maturity mismatch (short-term deposits vs. long-term loans to clean energy companies and projects) and an unattractive risk/return profile (non-bankable) of clean energy investments. In addition to addressing the risks through long-term oriented policy reforms (Campiglio, 2016) and long-term loan guarantees (Kenney and Hargadon, 2012), more structural policy measures might include more favourable macro-prudential regulation e.g. by increasing the risks weights for 'brown' loans (Campiglio, 2016; Polzin et al., 2017) and reforms that would enable banks to engage in more risky but also more productive lending practices responsibly, such as increased equity ratios (Elert et al., 2019; Thomä and Gibhardt, 2019).

Channelling the financial resources of *institutional investors (pension* funds*, insurance companies, sovereign wealth* funds) into clean energy requires clear environmental and economic policy signals for investors regarding the strategic framework for green investment (e.g. European Green Taxonomy). Clean infrastructure has been highlighted as one of the major areas to positively impact the COVID19 recovery as well as reduce CO_2 emissions (Hepburn et al., 2020). Policy makers could also encourage market participants to support the adoption and implementation of responsible investment principles or promote increased awareness and capacity building among key intermediaries such as stock exchanges, credit rating agencies, equity analysts and investment consultants (G20 Green Finance Study Group, 2016). To address liquidity constraints, legal barriers regarding intermediary fund structures such as YieldCos need to be solved. Finally policy makers need to support efforts to standardize contracts and project evaluation structures, e.g. creating aggregation and 'warehousing' facilities and improving market transparency (OECD, 2015a).

Many academic studies and reports highlight the important role of *state investment banks (SIBs)* for co-investing, signalling and information provision and risk reduction in the clean energy sphere (Geddes et al., 2018; Mazzucato and Penna, 2016; Mazzucato and Semieniuk, 2018). These provide an opportunity to address not only upstream (innovation-related) barriers, but also accelerate investments and lending to mature renewable energy projects and should hence be a corner stone of any policy mix (Röttgers et al., 2018). Moreover, SIBs allow governments to engage in financing the energy transition while potentially profiting from the spread between (low) borrowing costs for governments and (volatile but on average higher) returns on energy transition projects.

6.2. *Implications for financiers*

A number of implications for financiers follow from our analysis. First, investing in knowledge about climate change and clean energy in the form of human capital allows for better risk and return assessment across the board (e.g. Ghosh and Nanda, 2010; IRENA, 2016). Following sustainable/responsible investment practices and joining the respective networks is an obvious way of approaching this. Initiatives promoting socially responsible investments from within the sector (such as pension funds and sovereign wealth funds) that base their investments also on ESG criteria could be scaled up (G20 Green Finance Study Group, 2016).

Second, financiers should try to engage and work with (semi-)public investors such as the European Investment Bank (EIB) or sovereign wealth funds that have the capacity and knowledge to carry out the due diligence or take the first loss in case of underperformance of an energy transition investment. Almost all scenarios predict an increase in the share of clean energy from the main RE sources wind, solar and biomass. To be part of that transition seems a good thing. But sharing risks with public investors is a way to do so in a responsible way.

Thirdly, financiers need to develop innovative financial products to bundle small tickets into larger funds, because scale and due diligence costs are too often barriers to investments in clean energy companies, projects and infrastructures. Structured finance can help to increase the volume of investment by reducing such due diligence costs. These mechanisms can also help secure renewable energy assets for trading on capital markets (IRENA, 2016).

And finally, financial institutions should develop and adopt a methodology to standardize the assessment of projects/companies or intermediate channels such as green/climate bonds or YieldCos (e.g. European Green Taxonomy). This would reduce transaction costs and thus increase the feasibility of smaller investments, even by institutional investors such as pension funds or insurance companies. This will prove to be especially important since many of the scenarios require decentralized investments into energy efficiency such as retrofitting buildings.

CRediT authorship contribution statement

Friedemann Polzin: Conceptualization, Methodology, Data curation, Investigation, Visualization, Project administration, Funding acquisition, Writing - original draft, preparation, Writing - review & editing. **Mark Sanders:** Investigation, Writing - original draft, preparation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendices.

Appendix A.1: Clean energy investment needs for Europe

We compare investment requirements produced by a range of models under a scenario that takes current pledges of national government into account with scenarios that stay below 2 °C global warming. Total investments for these scenarios range between 94 and 258 USDbn annually and include investments in power generation, transmission/distribution and energy efficiency. For a detailed description of the models and scenarios, please see Appendix A.2. To better understand the investment dynamics in these models we disentangle these numbers for RD&D and deployment of the major technologies using five major integrated assessment models and the IEA WEM following McCollum et al. (2018).

Energy supply R&D investment needs (upstream/innovation).

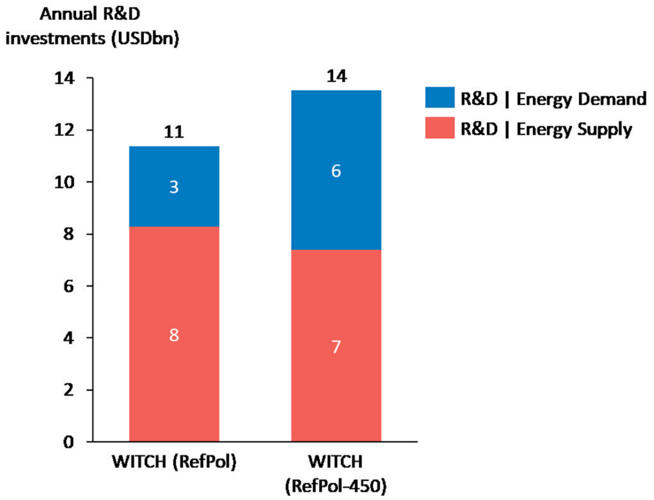

Fig. A.1 Annual average R&D investments in energy supply and total (2010–2050), USDbn (2005 USD).

Energy efficiency and fossil-fuel investments (downstream/diffusion).

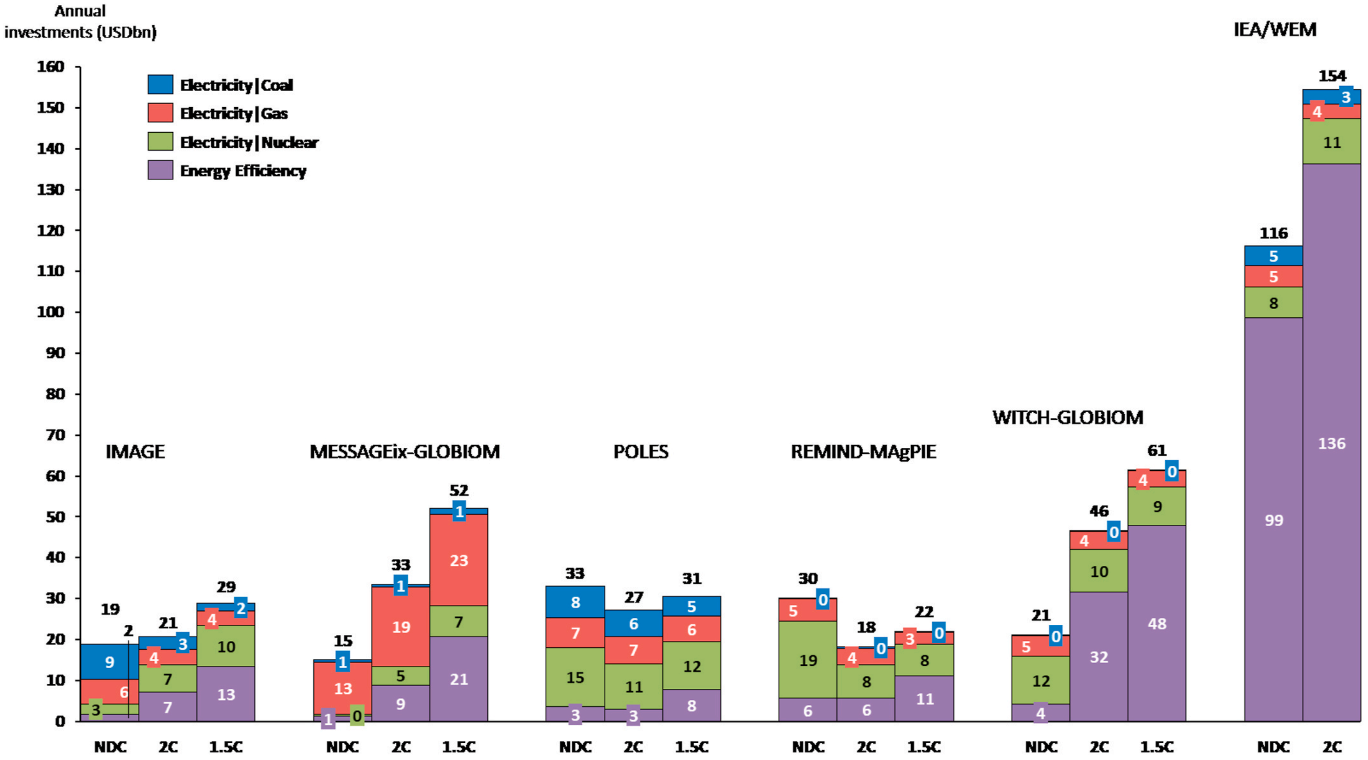

Fig. A.2 Annual average investments in energy efficiency and fossil fuel -based electricity supply across five IAMs (2016–2050, USDbn (2015 USD).

RE investment needs incl. transmission/distribution and storage.

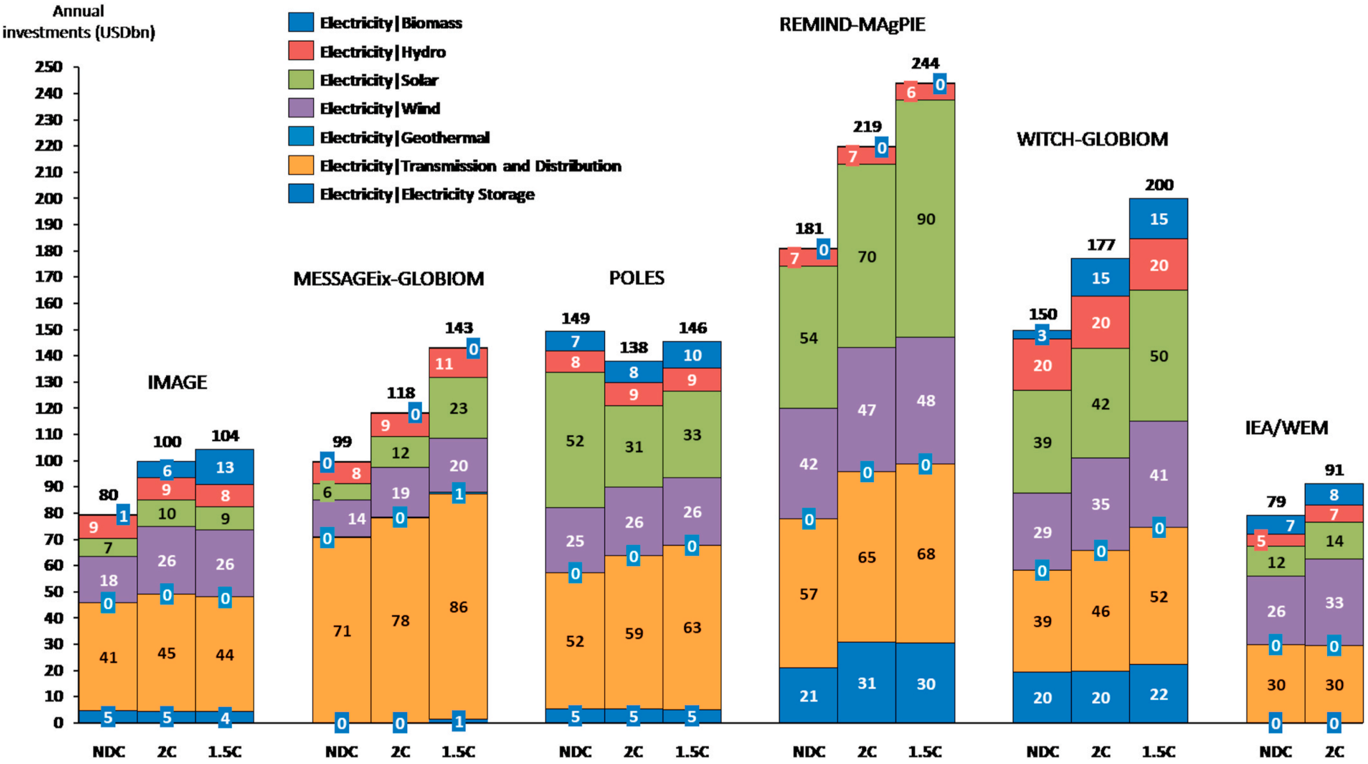

Fig. A.3 Average annual investment needs across 5 IAMs and scenarios (renewable energy technologies incl. transmission/ distribution and storage), (2016–2050), USDbn (2015 USD).

Appendix A.2: IAM description

Table A.1 Annual Investment needs across models and scenarios and model description

Model	New policies/ NDC	2°/ (comp).	1.5°/ (comp).	Time	Project	Technologies	Main features	Policy	Sources
IEA/WEM	195	245	–	2014–2035	WEO/ WEIO	Bioenergy, Hydro, Wind (onshore + offshore) Solar PV, Gas, Coal, Energy efficiency, transmission, distribution	International Energy Agency (World Energy Model) Large-scale simulation model designed to replicate how energy markets function, trends in demand, supply availability and constraints, international trade and energy balances by sector and by fuel, technological learning curves, investment requirements in the fuel supply chain to satisfy projected energy demand	Energy and climate-related policies (IEA policies and measures database)	(IEA, 2015; International Energy Agency, 2014).
IMAGE	99	121	133	2010/2016-2050	LIMITS CD-Links	Renewable energy, fossil fuel energy, nuclear energy and energy efficiency, transmission, distribution, storage	IMAGE (Integrated Model to Assess the Global Environment), comprehensive ecological-environmental model framework, simulation of long-term trends, 26 world regions, inertia and learning-by-doing in capital stocks, depletion of the resource base, technology development, and trade between regions,	Climate policies: e.g. carbon pricing, taxes, renewable energy targets, efficiency standards, reduced deforestation, non-CO2 reduction measures	IIASA Database (LIMITS) IIASA Database (CD-Links) https://www.nature.com/articles/s41560-018-0179-z McCollum et al. (2018) Supplementary information
MESSAGEix-GLOBIOM	114	151	195	2010/ 2016–2050)			MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact), linear programming energy engineering model with global coverage, medium- to long-term energy system planning, energy policy analysis, and scenario development	Policies via link to aggregated macro-economic model MACRO	
POLES	182	165	177	2010/2016-2050			POLES (Prospective Outlook on Long-term Energy Systems) model, global partial equilibrium simulation model of the energy sector, annual step, covering 38 regions worldwide (G20, OECD, principal energy consumers) plus the EU, learning effects captured	Energy efficiency, support to renewables, energy taxation/ subsidy, technology push or prohibition, access to energy resources,	
REMIND-MAgPIE	211	237	266	2010/2016-2050			REMIND (Regional Model of Investment and Development), energy-economy general equilibrium model, ramsey-type growth model with perfect foresight to project growth, savings and investments, full capacity vintage structure energy system, technological	Several energy sector policies are represented explicitly, including energy-sector fuel taxes and consumer subsidies	

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(*continued*)

Model	New policies/ NDC	2°/ (comp).	1.5°/ (comp).	Time	Project	Technologies	Main features	Policy	Sources
							learning of emergent new technologies		
WITCH	171	223	261	2010/2016-2050			WITCH (World Induced Technical Change Hybrid), integrated assessment model designed to assess climate change mitigation and adaptation policies, regional game-theoretic setup, endogenous treatment of technological innovation for energy conservation and decarbonization	Several climate and energy policies, R&D investments directed towards either energy efficiency improvements or development of carbon-free breakthrough technologies	

Notes: International Energy Agency (IEA), World Energy Outlook (WEO), World Energy Investment Outlook (WEIO), National determined contributions (NDC), World Energy Model (WEM).

Appendix A.3: Demand and supply of energy finance in Europe

Table A.2 Finance demand across scenarios and technologies

Technology	Demand annual 2° comparable. Scenarios: Lower bound (USDbn)	Demand annual 2° comp. Scenarios: Upper bound (USDbn)	Demand annual 2° comp. Scenarios: Average (USDbn)
Energy supply	7.4	7.4	7.4
Energy supply and demand	13.5	13.5	13.5
Energy efficiency	3	136	69.5
Nuclear	3	12	7.5
Gas with and without CCS	4	20	12
Wind	19	50	34.5
Solar PV	7	73	40
Hydro	7	20	13.5
Biomass with and without CCS	0	15	7.5
Transmission & distribution	31	80	55.5
	88.52	386.52	237.52

Table A.3 Finance supply across sources

Source	Supply: Lower bound (USDbn)	Supply: Upper bound (USDbn)	Supply: Average (USDbn)
RD&D finance	0.37 (average 2014–2017)	1.45 (average 2014–2017)	0.91
Small- and distributed finance	0.08 (average 2014–2017)	2.03 (average 2014–2017)	1.055
VC and private equity	2.58 (average 2007–2015)	4.61 (average high-tech 2007–2015)	3.59
Bank finance (debt)	3.03 (average 2002–2012)	38.33 (growth loans 2017–2018)	20.68
Sovereign wealth funds	1.76	104.7 (growth AUM, 2017–2018)	53.23
Pension funds		77.06 (growth AUM, 2016–2017)	61.17
Insurers	(average 2007–2013)	158.16 (growth AUM, 2016–2017)	85.42
State investment banks	5.20 (2004–2018)	60.35 (2018)	32.78
Green/climate bonds	101.8 (average 2014–2018)	191.22 (growth AUM, 2016–2017)	146.51
Public equity	2.41 (2002–2012)	221.54 (growth market capitalization 2014–2018)	111.98
	117.24	859.45	517.33

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