Diss. ETH Nr. 26778

The role of finance in mitigating climate change: Insights for public policy

A dissertation submitted to attain the degree of

DOCTOR OF SCIENCES of ETH ZURICH

(Dr. sc. ETH Zurich)

presented by

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2020

Table of contents

Acknowledgements

I am grateful to everyone who surrounded me over the past years for their support, laughter, and patience with me. Most of all, I am thankful for the continued support I receive from my partner in crime Seraina in embarking and concluding this journey. Her comments and ideas have been invaluable and her positive spirit often reminds me to keep going and see the bright side in moments when this is difficult.

I would not have embarked on this journey were it not for my good friend Lotte, who shared the job ad with me and said, ‘C’mon Flo, this is exactly what you have been wanting to do!’ Friends matter. I also would have not been able to do this were it not for the enthusiasm, ideas, and positive attitude of Tobi and his great leadership of the Energy Politics Group. Thank you! Also, I owe a big thank you to Bjarne, who has helped me tremendously to structure my thinking and make progress in this PhD.

After all, although single-authored, a PhD is always a team effort. This effort would not have been possible without the numerous people who accompanied me—professionally and personally—over the years, including the unconditional support of my family. Thank you all. Special thanks goes to Anna, Evan, Bjarne, Nico, and Seraina who have read through earlier drafts of this PhD and provided valuable comments and suggestions.

Looking out of the window, I see alpine choughs circling above a plateau against the backdrop of cloudy mountain forests. What lies ahead after this PhD is somewhat cloudy too, it will undoubtedly involve new adventures and new ties with people who I have the privilege to accompany. The first toast after completing this PhD will go to all those ties!

Sent, 30 March 2020

Abstract

Avoiding runaway climate change is one of the biggest challenges of the twenty-first century. Despite widespread calls for action from both activists and the economic elite at the World Economic Forum, greenhouse gas emissions continue to rise and we are on track to overshoot climate targets by 29-32 Gt CO_2eq in 2030. Changing this trajectory will require the rapid and deep decarbonisation of our economies, whereby decarbonising electricity generation is a key component in this endeavour.

Accordingly, any pathway consistent with limiting global warming to below 2°C above pre-industrial levels requires large-scale deployment of renewable energy. In turn, this requires an increase in total energy investment and a massive shift of investment from fossil fuels to renewable energy. Finance, therefore, has two levers to support this transition. First, by ramping up investment in low-carbon infrastructure and renewable energy and improving the financing conditions for such projects. Second, by reducing investment in high-carbon infrastructure and fossil fuels and worsening the financing conditions for such projects. This dissertation is concerned with the first lever.

Improving financing conditions is particularly important for renewable energy due to the associated capital-intensity compared to fossil fuel-based electricity generation. However, empirical research on renewable energy financing conditions, dynamics over time, factors for change, and the effects of policy is rare. Researchers and policymakers are, therefore, left in the dark regarding the dynamic role of finance in energy transitions.

In this dissertation, I approach this knowledge gap with mixed methods to study the history of renewable energy finance for mature technologies (onshore wind and solar PV) in mature markets (Germany, Italy and the UK). In doing so, I aim to develop an in-depth understanding of renewable energy finance and its interactions with public policy. In addition, I take a broader look at countries' climate finance responsibilities. Theoretically, I draw on two key concepts in this dissertation: the efficient market hypothesis and the adaptive market hypothesis.

Four key contributions emerge from the findings of the individual papers. First, this dissertation identifies policy designs that are particularly effective in reducing renewable energy investment risk and, thus, in spurring renewable energy deployment. Second, this dissertation provides empirical evidence on the state and dynamics of financing conditions. I find a pronounced improvement in financing conditions for onshore wind and solar PV accompanied by declines in investment risk over time. Furthermore, drivers conducive to improving financing conditions are identified, which is crucial for policymaking. Based on these insights, I suggest that adaptive market behaviour may play a role in renewable energy finance through certain dynamic processes, such as path dependency, learning and ecosystem effects. Third, this

dissertation shows that current energy system models do not sufficiently take these dynamics into account which may lead to biased policy implications. Fourth and finally, this dissertation takes a broader look and suggests a mechanism to distribute climate finance responsibility among the parties of the Paris Agreement. The mechanism puts special emphasis on incentive compatibility and provides a benchmarking tool to assess current climate finance pledges.

From these contributions I derive insights for policymaking. First, policymakers must pay attention to the design of renewable energy policies and their effects on investment risk. Credibility, constant monitoring and evaluation, standardised procedures, and common design elements across policies (and policy areas) are important for policy effectiveness. Second, policymakers could use these insights to commit to automatic mechanisms instead of ad hoc policies in other areas. For example, the proposed climate finance mechanism in this dissertation could provide a means to attain more credible climate finance pledges. Third, this dissertation suggests an important co-benefit of deployment benefits: by providing stable revenues, the policies automatically reduce financing costs as well as help drive down technology costs. To ensure their effectiveness, policymakers must focus on sharing data and expertise in order to establish a technology's track record and facilitate investment by reducing investment risk. Finally, policymakers must consider advice that explicitly takes the dynamics of financing conditions into account. For example, models used to plan renewable energy deployment or to choose electrification approaches must accurately reflect differences in financing conditions in order to produce meaningful policy insights.

Zusammenfassung

Die Verhinderung eines unkontrollierbaren Klimawandels ist eine der größten Herausforderungen des einundzwanzigsten Jahrhunderts. Trotz vielzähligen Handlungsaufrufen von Aktivisten, Wissenschaftlerinnen und der Wirtschaftselite auf dem Weltwirtschaftsforum in Davos steigen die Treibhausgasemissionen weiter an: Wir sind auf dem Weg, die Klimaziele bis 2030 um 29-32 Gt CO_2-äquivalente zu verfehlen. Um diesen Kurs zu ändern, ist eine rasche und tiefgreifende Dekarbonisierung unserer Volkswirtschaften erforderlich, wobei der Stromerzeugung eine Schlüsselrolle zukommt.

Entsprechend sieht jedes Szenario, welches die globale Erderwärmung auf unter 2°C über dem vorindustriellen Niveau begrenzt, den grossflächigen Einsatz erneuerbarer Energien vor. Dies wiederum erfordert eine massive Verlagerung der Investitionen von fossilen Brennstoffen auf erneuerbare Energien und eine Erhöhung der Gesamtenergieinvestitionen. Die Finanzwelt hat daher zwei Hebel um die Dekarbonisierung zu unterstützen. Erstens die Erhöhung der Investitionen in kohlenstoffarme Infrastruktur und erneuerbare Energien sowie die Verbesserung deren Finanzierungsbedingungen. Zweitens die Verringerung der Investitionen in kohlenstoffreiche Infrastruktur und fossile Brennstoffe sowie die Verschlechterung deren Finanzierungsbedingungen. Diese Dissertation befasst sich mit dem ersten Hebel.

Die Verbesserung der Finanzierungsbedingungen ist für erneuerbare Energien aufgrund ihrer Kapitalintensität, im Vergleich zur Stromerzeugung auf Basis fossiler Brennstoffe, besonders wichtig. Empirische Forschung zu den Finanzierungsbedingungen, der Dynamik über Zeit, den Faktoren für Veränderungen und den Auswirkungen regulatorischer Rahmenbedingungen ist jedoch selten. Forscher und politische Entscheidungsträgerinnen verfügen daher über unzureichendes Wissen in Bezug auf die Rolle von Finanzierungsbedingungen in der Energiewende.

In dieser Arbeit nutze ich sowohl qualitative als auch quantitative Methoden, oftmals kombiniert, um die Entwicklung der Finanzierung erneuerbarer Energien für etablierte Technologien (Wind auf Land und Photovoltaik) in entwickelten Märkten (Deutschland, Italien und Grossbritannien) zu untersuchen. Dabei versuche ich, ein vertieftes Verständnis der Finanzierung erneuerbarer Energien und ihrer Wechselwirkungen mit der Politik zu entwickeln. Darüber hinaus betrachte ich die Klimafinanzierung und die Verantwortung einzelner Länder, einen Beitrag dazu zu leisten. Theoretisch stütze ich mich in dieser Dissertation auf zwei Schlüsselkonzepte: die Hypothese effizienter Märkte und die Hypothese adaptiver Märkte.

Aus den Ergebnissen der einzelnen Publikationen ergeben sich vier Schlüsselbeiträge. Erstens identifiziert diese Dissertation Politikmassnahmen, die besonders effektiv sind, um das Investitionsrisiko für erneuerbare Energien zu reduzieren und dadurch den Ausbau

erneuerbarer Energien zu fördern. Zweitens liefert diese Dissertation empirische Belege für die Entwicklung der Finanzierungsbedingungen. Sie stellt eine ausgeprägte Verbesserung der Finanzierungsbedingungen für Wind- und Solaranlagen fest, die mit einem Rückgang des Investitionsrisikos im Laufe der Zeit einhergeht. Darüber hinaus werden Treiber identifiziert, die eine Verbesserung der Finanzierungsbedingungen begünstigen, was für die Politikgestaltung von entscheidender Bedeutung ist. Auf der Grundlage dieser Erkenntnisse schlage ich vor, dass ein adaptives Marktverständnis helfen kann, Prozesse wie Pfadabhängigkeit, Lern- und Ökosystemeffekte bei der Finanzierung erneuerbarer Energien besser zu verstehen. Drittens zeigt diese Dissertation, dass aktuelle Energiesystemmodelle diese Dynamiken nicht ausreichend berücksichtigen, was zu verzerrten Politikempfehlungen führen kann. Viertens und letztens nimmt diese Dissertation einen breiteren Blickwinkel ein und schlägt einen Mechanismus vor, um die Verantwortung für die Klimafinanzierung unter den Parteien des Pariser Abkommens aufzuteilen. Der Mechanismus legt besonderen Wert auf Anreizkompatibilität und bietet ein Benchmarking-Instrument zur Bewertung der aktuellen Klimafinanzierungszusagen.

Aus diesen Beiträgen leite ich Erkenntnisse für die Politikgestaltung ab. Erstens sollten politische Entscheidungsträger den Effekten von Politikinstrumenten auf Investitionsrisiken ein besonderes Augenmerk schenken. Glaubwürdige Massnahmen, deren ständige Begleitung und Neubewertung, standardisierte Verfahren und gemeinsame Grundlagen über die verschiedenen Politikfelder sind wichtig für die Wirksamkeit der Massnahmen. Zweitens könnten politischen Entscheidungsträgerinne diese Erkenntnisse nutzen, um sich auf Mechanismen, anstatt auf ad-hoc Massnahmen festzulegen. Der vorgeschlagene Klimafinanzierungsmechanismus könnte beispielsweise ein Mittel für glaubwürdigere Klimafinanzierungszusagen sein. Drittens findet diese Dissertation ein wichtiger Mitnutzen von Einspeisevergütungen: Durch die Bereitstellung stabiler Einnahmen verringern die Massnahmen automatisch die Finanzierungskosten und tragen dazu bei auch die Technologiekosten zu senken. Die gemeinsame Nutzung von Daten und Fachwissen hilft diesen Prozess zu beschleunigen, da damit Technologien besser bewertet werden können und Investitionen erleichtert werden. Schliesslich sollten politischen Entscheidungsträgerinnen sicherstellen, dass Finanzierungsbedingungen in Entscheidungshilfen explizit berücksichtigt werden. Für aussagekräftige politische Empfehlungen sollten beispielsweise Modelle zur Ausbauplanung erneuerbarer Energien oder zur Auswahl von Elektrifizierungsansätzen unterschiedliche Finanzierungsbedingungen adäquat widerspiegeln.

‘The decisive moment’

Henri Cartier-Bresson (1932), Place de l’Europe, Gare Saint Lazare, Paris, France.

Source: KEYSTONE/MAGNUM PHOTOS

1 Introduction

The photo taken in 1932 in Paris accompanied me in various apartments and cities over many years. Here, it serves as an analogy to a system before a tipping point[1]. The photographer, Henri Cartier-Bresson, coined the term 'the decisive moment' and used it to describe his photographic principle[2]. Cartier-Bresson describes these moments as 'the simultaneous recognition, in a fraction of a second, of the significance of an event as well as of a precise organization of forms which give that event its proper expression'[2]. In these magical and ephemeral moments, Cartier-Bresson is convinced that entire future stories that are possible unfold before the eyes of the spectator. Put differently, the intensity of a single moment can convey the unfolding of a radically different future before that future becomes reality. The stillness of the mirroring pond lasts only fractions of a second until ripples change the scene and destroy the mirror. While the spectator knows that the scene is about to change radically, the future state of the system is unknown. The only certainty is that change will occur, and that the status thereafter will be more chaotic. Many scholars see our economic, social, and technical system at such a crossroads—potentially a tipping point—in view of the current threat of climate change. While the terminology varies from 'waves of disruption' (Johnstone et al., 2020) to 'sensitive intervention points' (Farmer et al., 2019) or 'social tipping dynamics' (Otto et al., 2020), what is common among these concepts is that they see a disruptive and self-reinforcing potential in the combination of technological change, policy responses, financing decisions, and social preferences/movements. This dissertation attempts to further our understanding of the role of finance in climate change and energy transitions. In particular, it suggests policies that leverage the role of finance in accelerating such tipping points towards a low-carbon system. Therefore, this dissertation sheds light on the questions of where capital for climate finance should come from, how investors make sense of an existing risk-return landscape and form their investment decisions, how the resulting financing conditions impact technology costs and low-carbon transitions, and how energy system models represent these dynamics.

1.1 Climate change and finance

Numerous commentators call avoiding runaway climate change the greatest challenge of the twenty-first century. In view of self-reinforcing climate tipping points, which may occur even earlier than predicted by climate models, climate scientists call for urgent action to reduce

[1] A tipping point is a critical threshold in a complex adaptive system, where a relatively small change (e.g. a policy) can trigger larger dynamics that are self-reinforcing (Farmer et al., 2019).

[2] He originally borrowed the expression from Cardinal de Retz, who wrote in the seventeenth century, 'There is nothing in the world that does not have a decisive moment'. The expression is also the English title to his first book published in 1952 (original French title: 'Images à la Sauvette'), which is one of the most important books of twentieth century photography. This is a quote from the book's introduction.

greenhouse gas (GHG) emissions (Lenton et al., 2019). In order to coordinate actions to mitigate GHG emissions and adapt to climate change, the international community negotiated the Paris Agreement in 2015[3]. By early 2020, 189 of the 197 parties to the United Nations Framework Convention on Climate Change (UNFCCC) have ratified the agreement. The main goal of the Paris Agreement is to limit global warming to well below 2°C above pre-industrial levels. In order to do so, parties (i.e. countries) to the agreement submit nationally determined contributions (NDCs), which outline their national plan to comply with the goal. In addition, 65 countries pledged to 'work towards achieving net zero emissions by 2050' at the 2019 UN Secretary General's Global Climate Action Summit (United Nations Environment Programme, 2019) with certain countries (such as France and the United Kingdom) enacting national laws on the pledge and others (like Switzerland) issuing commitments from the federal government.

Despite these pledges and 185 submitted NDCs (UNFCCC, 2020), global GHG emissions continue to rise. This is likely to produce an emissions gap of 29-32 Gt CO_2eq by 2030 (54% of estimated global 2030 emissions) if all countries are fully compliant with their NDCs (United Nations Environment Programme, 2019). The gap between ambition and reality underlines the challenge of the massive transformation required. Pathways aligned with limiting global warming to well below 2°C above pre-industrial levels require 'rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems' (IPCC, 2018). While all these sectors require change, the transformation of electricity generation is a priority from an emissions' perspective. Figure 1 depicts that energy and transport together account for two-thirds of CO_2 emissions, with electricity generation (main plant activity) the largest contributor at just above 11 Gt in 2015[4]. Moreover, the decarbonisation of the transport sector (7.7 Gt) will induce large additional electricity demand if it takes place through electrification. Hence, decarbonising electricity generation emerges as a key priority to close the emissions gap. Solar photovoltaics (PV) and wind energy will play crucial roles in this transformation (Chu and Majumdar, 2012). These transformations are not only required to meet the goals of the Paris Agreement but they are also crucial to achieving the broader Sustainable Development Goals (SDGs) (Fuso Nerini et al., 2018; Sachs et al., 2019). For example, SDG 7 requires doubling renewable energy (RE) shares, which will produce various related co-benefits, such as improved air quality and better health, linking climate change mitigation and RE deployment to numerous other SDGs (Fuso Nerini et al., 2019).

[3] The international process began in 1992 with the Declaration of the UNFCCC (Earth Summit in Rio de Janeiro), which entered into force in 1994.

[4] Electricity generation and heat remain the largest contributing sectors at roughly 25% when GHG emissions overall (CO2eq) are considered (IPCC, 2014).

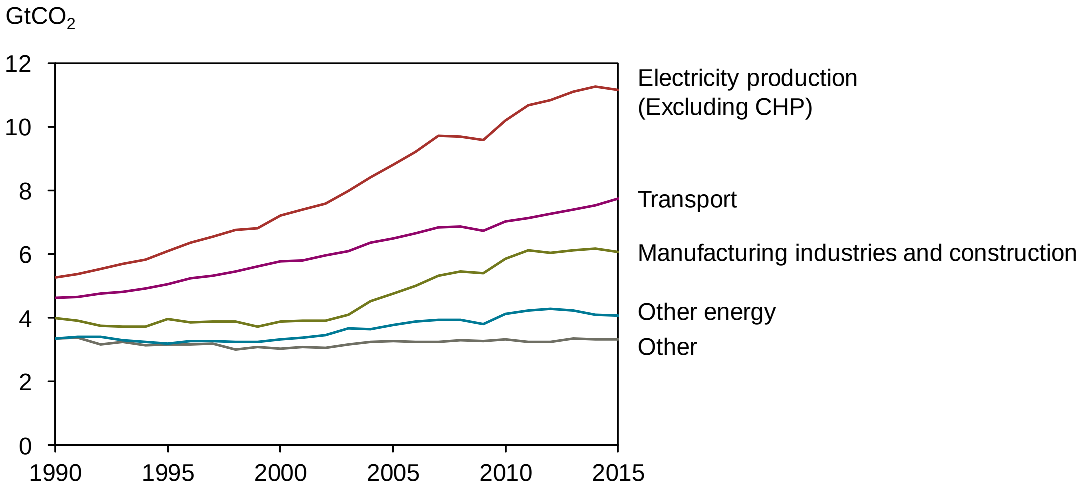

Figure 1: Annual CO_2 emissions by sector. Own illustration based on IEA data (IEA, 2019)*. 'Other energy' includes combined heat and power (CHP) plants, heating plants, and other energy industry's own use. 'Other' includes residential, commercial and public services, fishing, agriculture and forestry, and unspecified.*

Addressing the described emissions gap and progressing towards achieving the SDGs require the redirection of private and public financial flows: First, investment in low-carbon assets must increase; second, investment in carbon-intensive assets must decrease.

First, decarbonisation and adaptation to and mitigation of climate change will generally require investment. In order to cater to this need, developed countries have pledged to contribute USD 100 billion annually in climate finance from 2020 onwards. The pledge, formalised at the COP16 in 2010 in Cancun, Mexico, has become known as the climate finance commitment (Peake and Ekins, 2017). However, investment needs for new infrastructure in a decarbonised economy are far greater. For example, the International Energy Agency (IEA) estimates that annual energy investments alone must double from USD 1.8 to USD 3.5tn until 2050, of which a third would have to be in power generation (OECD/IEA and IRENA, 2017). Hence, academics and policymakers agree that over and above the climate finance commitment, large-scale private investment is required (IPCC, 2014; Iyer et al., 2015; Kaminker and Stewart, 2012; Polzin, 2017). Indeed, private investment is increasingly flowing to low-carbon assets, such as RE. Between 2013 and 2016, over USD 1tn have been invested in RE, the vast majority in solar PV and wind power (IRENA and CPI, 2018).

Second, financial flows must be redirected away from fossil fuels (FFs) and carbon-intensive infrastructure, because a large share of known oil, gas, and coal reserves must remain unused from 2010 to 2050 to meet the goals of the Paris Agreement (McGlade and Ekins, 2015). Despite a few phasing-out initiatives, such as the 'powering past coal alliance' (Jewell et al., 2019), numerous countries continue to spend substantial public money on FF subsidies (Coady et al., 2019), which has direct negative effects on the climate (Erickson et al., 2020). In addition to the need for the redirection of public investment and subsidies, private capital plays an important role as well. Partially due to ethical considerations and partially due to financial considerations and the risk of stranded assets (Dietz et al., 2016; Mercure et al., 2018), private investors are beginning to shift their portfolios away from FFs. By early 2020, almost 1100 investors had divested close to USD 14tn, including large institutional investors (Boermans and Galema, 2019). However, the evidence on the impact of such withdrawals on companies' actions remains scarce (Kölbel et al., 2019), with some evidence that it could become more difficult for oil and gas companies to raise new capital (Cojoianu et al., 2019).

To summarise, any pathway consistent with achieving the Paris goals and the SDGs requires decarbonizing electricity generation and, hence, a large deployment of RE. In turn, this requires a massive shift of investment from FFs to RE and an increase in total energy investment. Finance has two levers to support this transition. First, ramping up investment in low-carbon infrastructure and RE and improving the financing conditions for such projects. Second, reducing investment in high-carbon infrastructure and FFs and worsening the financing conditions for such projects. The objective of this dissertation is to understand the first lever and identify policies which incentivize and enable the financial industry to move towards RE. It primarily focuses on private investment, which forms the backbone of RE investment (see section 2.4).

1.2 Research framework

The previous section demonstrated the importance of finance in addressing climate change and enabling the energy transition towards low-carbon infrastructure and RE. Given the persisting emissions gap, policies are required to accelerate the transition.

Therefore, I address the following overall research question in this dissertation:

> How should policy be designed to support low-carbon finance and accelerate the transition towards a low-carbon infrastructure and RE in particular?

This dissertation is concerned with financing climate change mitigation in general and mainly analyses RE finance. Apart from the first contribution to climate finance, it focuses on private investment in utility-scale onshore wind and solar PV, the two most deployed non-hydro RE, which are key to decarbonising electricity generation (section 1.1). I analyse financial intermediaries in RE finance, a crucial building block to match projects and capital as well as manage risks (section 2.1). Two theories, the efficient and the adaptive market hypotheses, turn out to be particularly helpful in describing the observed patterns (section 2.2.). In the analysis, I focus on financing stages after the commercialisation of onshore wind and solar PV (section 2.3) and predominantly analyse project finance structures (section 2.4). Finally, this dissertation aims to distil insights regarding the options and effectiveness of public policy interventions in the field of climate change and RE finance (section 2.5).

Figure 2 depicts the overarching research framework and the contributions of each paper, which are listed in Table 1. On the left, the figure presents stylised policy domains that policymakers can utilise. All policy domains can be applied in multilateral, national, or sub-national contexts, whereas the focus of this dissertation is on multilateral climate policy (Paper 1) and national RE policies (Papers 2-4). On the right, the figure presents the low-carbon and RE sector and the financial sector. The former comprises of actors that run low-carbon infrastructure or projects as well as manufacture, install, and operate RE projects. The latter comprises actors that assess and finance these assets (e.g. public or private debt or equity investors, law firms, etc.). In this framework, Paper 1 investigates climate finance contributions reflecting the goal negotiated within the UNFCCC. It develops a burden-sharing mechanism to distribute responsibilities among countries in their contribution to global climate finance. Paper 2 provides a literature review of the empirical evidence on policy effectiveness with regard to RE investment. Papers 3 and 4 analyse two aspects of the interaction between RE and the financial sector. Paper 3 analyses the financing conditions of German onshore wind and solar PV projects over time to identify the effect of changes on the levelised cost of electricity (LCOE) and the drivers of change. Paper 4 links these changes to changes in investment risk in German, Italian, and UK projects and uses investor interviews to identify drivers of investment risk. Finally, Paper 5 sheds light on the importance of accurately depicting RE and financial sector interactions in energy system models and indicates the potential bias in such models when ignoring these interactions.

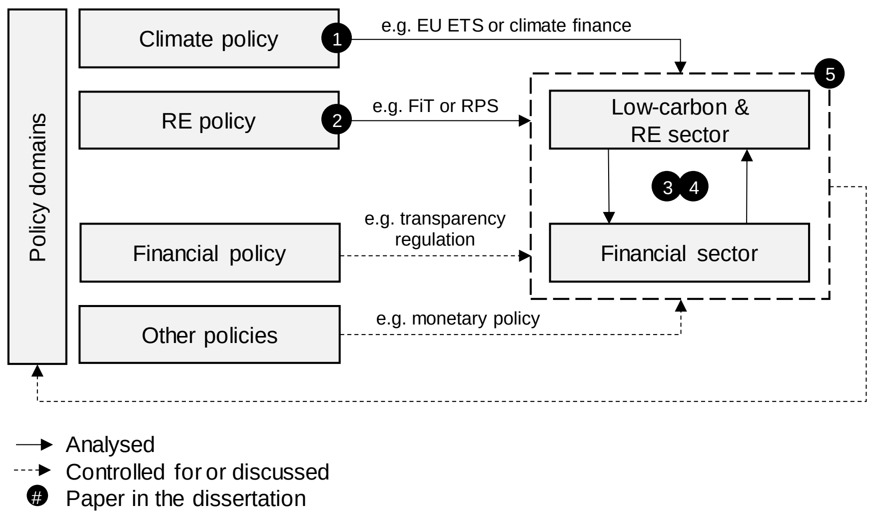

Figure 2: Research framework for this dissertation with qualifying papers[5].

These papers address important gaps in the literature. Empirical research on financing conditions, dynamics over time, factors for change, and the implications for policy is rare. The

[5] Financial policies are not covered in this dissertation, but refer to policies that are 'public policies addressing the financial sector with the aim of making finance flows consistent with the commitments of the Paris Agreement' (Steffen, 2020). Examples include regulatory product frameworks (e.g. green bonds) or risk disclosure (e.g. climate).

reasons for this include a lack of data and a lack of interdisciplinarity. First, financing conditions for RE projects are often confidential and unavailable in curated data sets (see section 2.4). Consequently, the empirical researcher stands before the decision to collect data through direct contact with investors or to use proxies, such as RE company stocks (Donovan and Nuñez, 2012). Second, research on RE has, for a long time, been the domain of engineers and statisticians in estimating learning curves for RE and other technologies (Bolinger and Wiser, 2012; Kavlak et al., 2016; Nagy et al., 2013; Nemet, 2006; Qiu and Anadon, 2012) and building energy system models to represent RE (Bogdanov et al., 2019; Jacobson et al., 2017b, 2017a; Rogelj et al., 2015). Consequently, the research on reasons for reductions in technology cost and the research on representing such dynamics in models remains rather disconnected from questions of financing.

Using the framework in Figure 2, this dissertation addresses these two barriers by collecting novel data on financing conditions and using mixed methods in most papers. This dissertation is structured in the following manner. Chapter 2 provides the theoretical background for the analyses described in Figure 2. Chapter 3 describes the main methods used in the research papers, and Chapter 4 briefly summarises the results of each paper. Finally, Chapter 5 discusses the overall contributions to the literature, implications for policymakers, and avenues for further research. Hence, Chapters 3 and 4 are based on the papers in Annex I, while the other chapters provide an overarching framework.

Table 1: Overview of qualifying papers[6].

	Title	Authors	Case	Data	Method	Status
1	A dynamic climate finance allocation mechanism reflecting the Paris Agreement	Florian Egli, Anna Stünzi	Global climate finance responsibilities	NDCs of 164 countries and secondary data	Conceptual and quantitative	Published in *Environmental Research Letters* (2019)
2	How do policies mobilize private finance for renewable energy? A systematic review with an investor perspective	Friedemann Polzin, Florian Egli, Bjarne Steffen, Tobias S. Schmidt	Peer-reviewed evidence on policy effectiveness in Investment grade countries including four BASIC emerging economies; Brazil, China, India, South Africa	57 peer-reviewed quantitative papers and 39 peer-reviewed qualitative papers	Literature review of qualitative and quantitative evidence.	Published in *Applied Energy* (2019)
3	A dynamic analysis of financing conditions for renewable energy technologies	Florian Egli, Bjarne Steffen, Tobias S. Schmidt	Onshore wind and solar PV in Germany from 2000 to 2017	Financing conditions of 133 projects and RE investor interviews	Quantitative and qualitative	Published in *Nature Energy* (2018)
4	Renewable energy investment risk: An investigation of changes over time and the underlying drivers	Florian Egli	Onshore wind and solar PV in Germany, Italy and the United Kingdom from 2009 to 2017	40 RE investor interviews and financing conditions of RE projects	Qualitative and quantitative	Published in *Energy Policy (2020)*
5	Bias in energy system models with uniform cost of capital assumption	Florian Egli, Bjarne Steffen, Tobias S. Schmidt	Solar PV global with a focus on DRC, Italy, Peru, South Korea, South Sudan, Switzerland	LCOE input data for six countries	Modelling	Published in *Nature Communications* (2019)

[6] While not included separately as a qualifying paper, the Policy Brief *Egli, F., Steffen, B., & Schmidt, T. S. (2019). Learning in the financial sector is essential for reducing renewable energy costs. Nature Energy, 4(10), 835–836.* https://doi.org/10.1038/s41560-019-0482-3 is based on the results of Paper 3 and as such discussed in this dissertation as well.

2 Theoretical background

This chapter provides the theoretical background to the research framework presented in Figure 2; it is structured in the following manner. First, I provide the conceptual background to understand RE and climate finance by introducing the key functions of financial intermediation (section 2.1) and presenting two theories, the efficient market hypothesis and the adaptive market hypothesis, to explain the behaviour of financial actors (section 2.2). Second, I provide background information on the types of finance (section 2.3) and the state of RE finance (section 2.4) to back up the focus of the dissertation. Third, I discuss levers for policy intervention (section 2.5).

2.1 Financial intermediation and theory

Financing conditions for a project are determined through a process called financial intermediation. A financial intermediary (FI) is an 'entity that intermediates between the providers and users of financial capital' (Greenbaum et al., 2016). Essentially an FI—for example, a bank—brings together borrowers and lenders. The key reasoning for the existence of FIs is usually the presence of imperfect information[7]. FIs provide several functions, two of which are analysed in this dissertation: brokerage and qualitative asset transformation (Greenbaum et al., 2016).

Brokerage involves connecting buyers and sellers to facilitate a financial deal. Theoretically, it eliminates two information asymmetries—one before entering the contract and one after (see Figure 3). Adverse selection, first introduced by the later Nobel laureate George Akerlof, describes a situation where one party has an incentive to overstate before entering into a contract (e.g. a seller overstating product quality or a borrower overstating credit worthiness) (Akerlof, 1978). In an RE project, an FI would, for example, propose financing conditions based on an assessment of the revenue potential and the soundness of the resource estimation in order to ensure that there is no overstating. In this context, duplicated screening describes a process through which parties can resolve information asymmetry, but this comes at a prohibitive cost. In an RE project, several debt and equity investors may want to engage in a project. Instead of each investor screening each project individually, there is value in an FI providing the service to all parties. Finally, post-contract, brokerage helps to alleviate moral hazard. Moral hazard is a situation in which a party has signed a contract knowing that it will change its behaviour once the contract is in place. For example, a wind park operator could have spent extra effort on maintenance before signing a re-financing deal. If the deal is based on some past data, the financing conditions may be better than they would otherwise be, and

[7] Banks have further classic functions, such as creating money and safekeeping deposits (Thakor, 2019). However, in the context of RE investments, addressing information asymmetries between parties is the key function of FIs.

the operator could revert to low maintenance after signing the deal. In established markets with competition and vast data availability, moral hazard becomes somewhat less relevant. However, reducing it remains a key function of FIs.

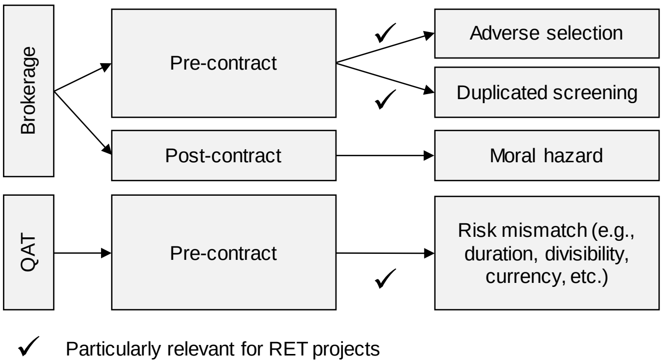

Figure 3: The main functions of a financial intermediary and relevance for RE projects. Own illustration, based on (Greenbaum et al., 2016)*. QAT stands for qualitative asset transformation.*

Qualitative asset transformation (QAT) describes the functions of an FI in matching the preferences of two parties to a contract. For example, QAT can involve maturity transformation or sizing. RE projects are typically financed for the duration of the support scheme (often approximately 20 years). More recently, new financing structures have been introduced, which extend beyond the period of guaranteed revenues under the support scheme. In general, however, not all investors may want to invest for the exact period for which an RE asset runs. For example, if a pension fund invests in an RE asset, it engages in a classic maturity transformation: it receives a constant inflow of money from future retirees, which the pension fund has to pay out at a subsequent point in time. Sizing is also common. Often, sizing refers to splitting large investments into several smaller tickets to make it more accessible to smaller investors. While this type of sizing is important for new large-scale projects, such as offshore wind, the opposite (combining small projects into larger tickets) has been crucial in the early phases of onshore wind and solar PV deployment.

2.2 Efficient versus adaptive markets

This characterisation of FIs was made on the assumption that through FIs the market can become efficient and information asymmetries can be resolved. Therefore, the classification followed the efficient market hypothesis (EMH), which stipulates that ‘in an efficient market, the price of an asset fully reflects all available information about that asset’ (Lo, 2017). Using an example from above, in the case of an RE investment, this would imply that the information asymmetry between a project developer and an investor (e.g. a pension fund) could be resolved completely. In other words, through the FI, the pension fund can accurately assess all the risks associated with the RE project and the project developer gets the credit on conditions that accurately reflect the project risk.

However, scholars have also proposed alternatives to the EMH. In an effort to organise them, Grubb, Hourcade, and Neuhoff (2013) use three categories to describe different approaches of understanding the financial system: First, individual behaviour and cognition; second, rational actors and market efficiency; and third, evolutionary and institutional system changes. Economic literature has typically evolved around the first two categories. The first is the domain of behavioural economics, which established concepts, such as risk aversion. The second usually employs general equilibrium models that assume rationality and market clearing (hence efficiency), with a few extensions into the third category by adding path dependencies to analyse the lack of investment and innovation in clean technologies (Acemoglu et al., 2012). Hall, Foxon, and Bolton (2017) took a first step in describing the role of finance in this third category; however, they mainly frame a research agenda in demanding that more needs to be done to understand 'how the features of capital markets influence system transitions and energy/climate policy'.

The adaptive market hypothesis (AMH) proposes an extension to the EMH to include the third category. The AMH was pioneered by Andrew Lo and builds on the work of Nobel laureate Herbert Simon. Simon postulated that instead of choosing optimally, most human beings choose options that they deem 'good enough' according to heuristics (Lo, 2017; Simon, 1955). In these choices, they are constrained by their skills, values, and knowledge. Lo builds on the notion of heuristics and introduces adaptive behaviour, which describes constant trial and error, incorporating positive and negative feedback, and learning from this feedback to build heuristics (Brennan and Lo, 2012, 2011; Lo, 2017). As this learning behaviour has been developing along the evolution of humans, irrational or maladaptive behaviour can develop if there is no or weak feedback. In his book, Lo explains the connection between heuristics and maladaptive behaviour as follows: 'Under the AMH, behavioural biases abound, and for good reason. They are simply heuristics we have adapted from nonfinancial context that we misapply when we use them in financial settings: maladaptive behaviour, in other words.' The empirical part of this dissertation finds evidence of such heuristics being at play and delaying the provision of low-cost financing to novel RE technologies. It takes, amongst other factors, project experience, feedback, internal processes and a functioning financing ecosystem for the RE financing industry to learn (e.g. learning-by-doing) and thereby re-evaluate existing heuristics to be able to improve financing conditions for novel RE technologies. This dissertation not only investigates how individual actors or organisations in the financial sector learn, which is typically the unit of analysis for the AMH, but it also investigates broader network and ecosystem effects in the financial sector. These 'industry-wide' effects are usually not considered by the AMH.

A case in point of such maladaptive behaviour is probability matching, which is observed empirically and which the following example illustrates. Imagine a coin toss that reveals heads in 75% of the tosses and participants survive if they choose correctly before the toss. In the first setup, each participant in a group of eight tosses a coin, thereby reflecting idiosyncratic risk. In this setup, the optimal choice for everyone is to pick heads and follow the rational choice. In the second setup, the same coin toss happens once and all participants receive the same result. Now, the optimal choice is to match probabilities (six choose heads, two tails), because the risk is systemic. Evolutionary situations often entail systemic risk, which is why we arguably still observe probability matching or adaptive behaviour in numerous markets. In essence, 'if we want to understand current behaviour, we need to understand the past environments and selective pressures that gave rise to that behaviour over time and across generations of trial and error' (Lo, 2017). This theoretical lens enables a characterisation of path dependent decision making, which is often present in RE finance, as revealed by the results of this dissertation. Hence, this dissertation draws on rational (EMH) and adaptive (AMH) behaviour theories to understand RE finance.

2.3 Types of finance

Depending on the maturity of a technology, different types of finance are required. While a few scholars have developed frameworks to allocate types of finance depending on the capital intensity and risk of a technology (Mazzucato and Semieniuk, 2018), most scholars use frameworks along the innovation chain of a technology. Figure 4 illustrates the evolution of a technology from basic R&D to mainstream and indicates the corresponding types of finance from public and private sources for each step.

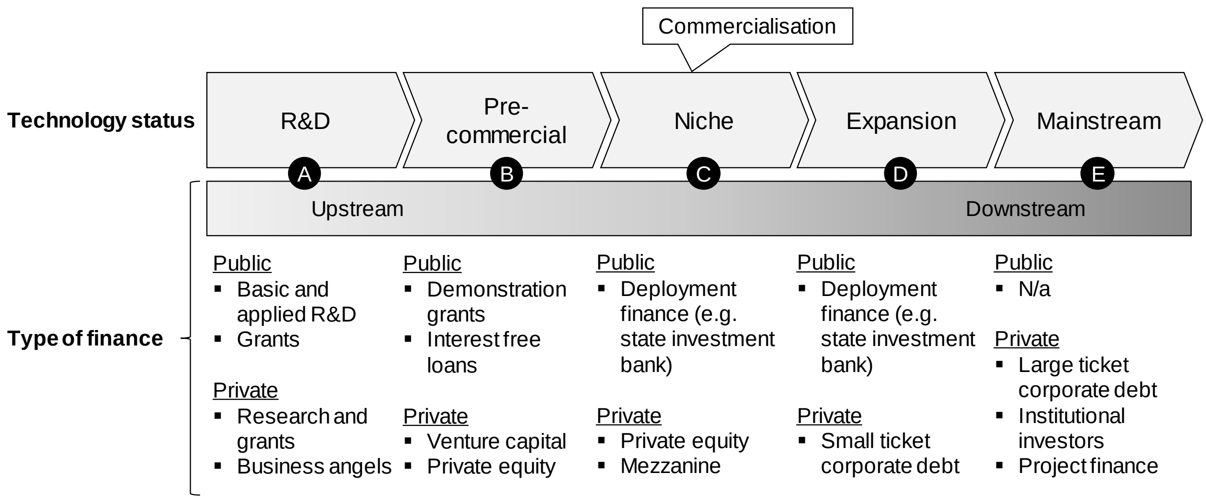

Figure 4: Type of finance. Technology status and type of finance are adapted from (Polzin, 2017; Polzin et al., 2017)*. Own illustration based on* (Bürer and Wüstenhagen, 2009; Grubb, 2004)*.*

In step A, grants and subsidies are the most common types of finance (Polzin, 2017) and public and private labs deliver R&D as part of their general budget. Attracting capital is difficult, because it is uncertain whether the technology will develop market potential. In step B, a technology must cross the 'valley of death', moving from demonstration to commercial viability (Grubb, 2004; Polzin et al., 2017). At this stage, venture capital (VC) and private equity (PE) invest in small start-up companies and large firms may continue internal funding from step A (Polzin, 2017). However, due to the capital intensity and difficulty to scale, VC and PE are less common in the energy sector compared to other sectors (Polzin et al., 2017). For the public sector, the 'valley of death' can be a reason to step in and provide demonstration grants or zero-to-low interest loans. In step C, a technology commercialises and mezzanine financing may begin to play a role because revenue prospects become clearer. However, due to technology and infrastructure lock-in, powerful incumbents and numerous other barriers, public financing may still be required for a technology to gain market shares (Polzin, 2017). In step D, a technology gains sufficient momentum through cost reductions, learning processes, and broad acceptance to challenge incumbents and existing technologies (Geels et al., 2017). While public deployment finance still plays a role, the window opens for smaller corporate debt, as the technology begins to gain market shares quickly. Solar PV projects in the early to mid-2000s would fall into this category, as they were unable to finance fully privately, but once there was some public assistance, corporate debt could be leveraged (cf. section 4.3). In step E, the technology becomes mainstream. As such, public finance is no longer required and international capital markets provide sufficient financing to scale further. At this point, large ticket corporate debt (e.g. large banks) begin joining the financing rounds and the projects become attractive to institutional investors (e.g. insurers, pension funds).

The major portion of this dissertation focuses on onshore wind and solar PV after commercialisation. It analyses the role of the financial sector in enabling these technologies to move from a niche to a technology in expansion or a mainstream technology depending on the market, thereby focusing on downstream capital. In particular, it investigates which policies enabled the financial sector to move through these steps faster in order to derive insights for policymakers aiming to accelerate the energy transition. These insights remain crucial, even though key technologies are transitioning into the mainstream because, as section 1.1 has shown, current private investment levels remain too low to achieve the goals of the Paris Agreement.

2.4 Renewable energy finance

Accompanying the progress in the maturity of technology, RE projects have enjoyed a remarkable inflow of investments in recent years. Figure 5 depicts that global annual investments in RE, excluding large hydro projects, are on a steady increase. From 2004 to

2018, annual RE investment roughly increased six-fold, reaching approximately USD 300bn. Over the previous decade (2010–2019), capacity investments totalled USD 2.6tn and total investments (including, e.g., research and development [R&D]) totalled USD 2.7tn. Figure 5 depicts that over 90% of RE capacity investments between 2010 and 2019 went to solar PV and wind projects. The figure also indicates that three-quarters of total RE investments are reported as asset finance, typically used to finance large-scale RE plants[8].

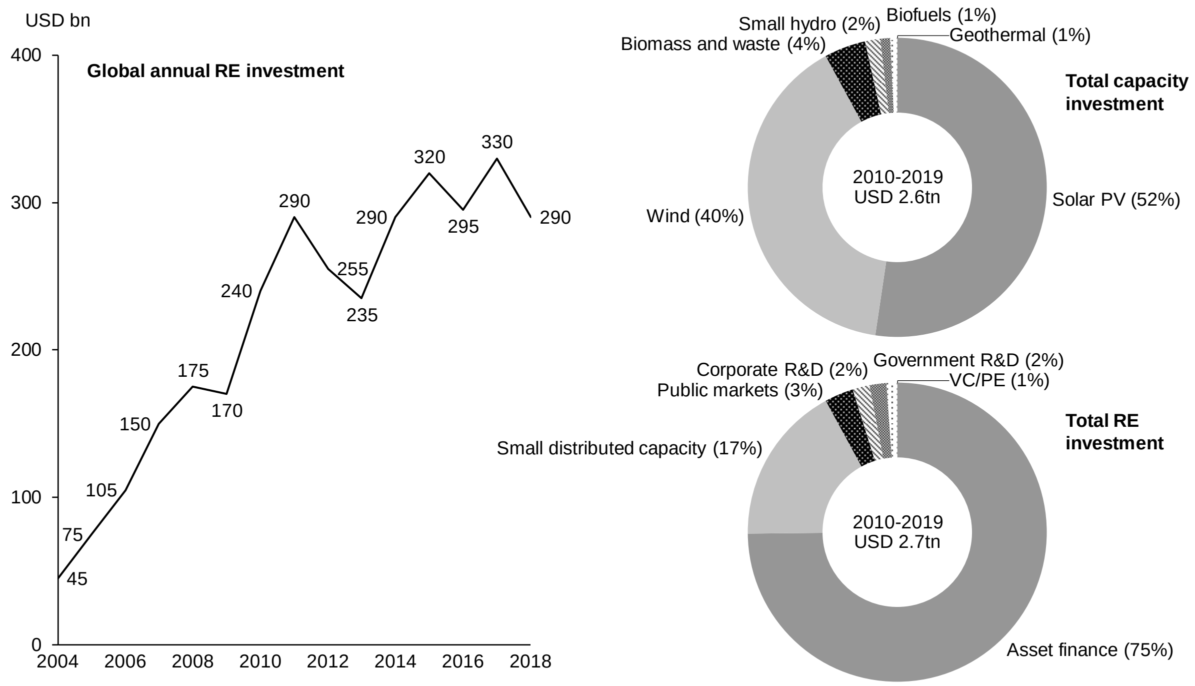

Figure 5: Historical trends in RE investment. Global annual RE investment (left); total capacity investment by technology (top right); total RE investment by category (bottom right). RE excludes large hydro. Own illustrations, based on BNEF data (Frankfurt School-UNEP Centre/BNEF, 2019)*.*

There are two major ways to finance new projects: on-balance sheet or off-balance sheet (Pinto and Alves, 2016). I refer to the former as corporate finance and to the latter as project finance, because off-balance sheet finance is usually contained in separate project-specific legal entities. The vast majority of total investment in advanced economies takes the form of corporate finance (Esty, 2004; Pinto and Alves, 2016). Estimates put the project finance share at just 10%–15% for markets like the US (Esty, 2004). In corporate finance, the firm (i.e. the corporation) receives a credit for a new project and guarantees for it with its assets and cash flows. In project finance, the sponsors establish a new legal entity, often a special purpose vehicle (SPV), to act as the guarantor. The credit is no longer guaranteed by the balance sheet of an existing firm but only by the project's cash flows and the asset itself. With regard to RE finance, the crucial difference is the limited recourse: creditors cannot rely on any assets

[8] Asset finance includes balance sheet finance, project finance, and project bonds.

beyond the project. Consequently, the SPV's cash flows must cover operating costs and the debt service (i.e. capital repayment and interest) at any time. As the remaining cash flows go to the project sponsors, both parties—sponsor and creditor—have an interest in verifying the solidity of the project's cash flows in order to service outstanding debt. Therefore, a project's financing conditions are directly tied to its investment risks.

Compared to the overall financing market, RE investments are more often realized in project finance structures. Figure 6 depicts that approximately 40% of total RE asset finance is realised off balance sheet in project finance structures. This share remains constant over time since around 2008. However, in early markets, the project finance share can be remarkably higher. For example, in Germany, 96% of large solar PV projects and 88% of large wind onshore projects between 2000 and 2015 were realized through project finance structures (Steffen, 2018). This setup is empirically appealing because the financing conditions can be analysed without having to adjust for the sponsor's balance sheet. The downside of analysing project finance is the lack of data, as project finance deals are over-the-counter (OTC)—by definition not on balance sheet and seldom traded publicly (see section 1.2).

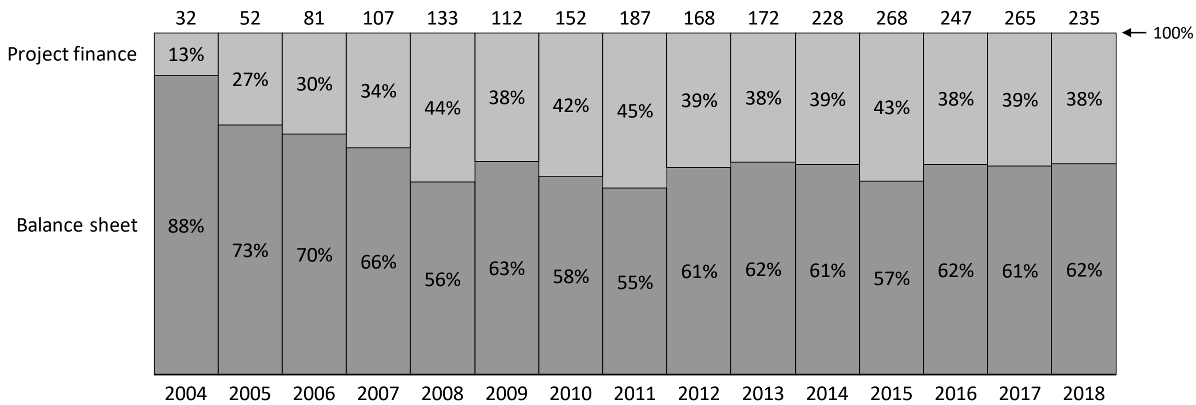

Figure 6: Type of financing for global renewable energy asset finance. Bonds and other, which are <1%, are not presented here. Own illustration based on BNEF data (Frankfurt School-UNEP Centre/BNEF, 2019)*.*

In practice, an investor demands a return that reflects the investment risk for each project. In its simplest structure, an investment consists of equity and debt, where the latter is repaid first in case of financial distress, which makes debt less risky. Debt and equity conditions and the ratio of debt to equity determine the overall cost of capital (CoC) of an investment project, as given in equation (1). Again, these conditions are only related directly to the project in project finance and vary depending on the project's underlying characteristics (e.g. technology, sponsors, regulatory framework, etc.)[9]. In general corporate finance, equity conditions may be

[9] Note that financing conditions encompass more than the CoC. While the CoC is the most common metric to measure the impact of financing conditions on LCOE, further financial indicators, such as the debt service coverage ratio (DSCR) or loan tenors (see papers for details), also reflect project risks and market conditions.

influenced by strategic considerations of a firm (e.g. internal hurdle rate) and the debt conditions may be influenced by the health of other business activities of the firm and its overall balance sheet.

$$CoC = K_E \frac{E}{V} + K_D \frac{D}{V}(1-T). \tag{1}$$

In equation (1), CoC denotes the cost of capital; *E* and *D* denote equity and debt investment, respectively; *V* signifies the total investment sum; K_E and K_D refer to cost of equity and cost of debt, respectively; and *T* represents the corporate tax rate. The leverage is equal to *D/V*.

Equation (2) indicates how the CoC is included in the standard calculation of lifetime electricity cost—the LCOE. C_0 denotes the initial investment cost (CAPEX); C_t denotes the operating and maintenance costs (OPEX) occurring in each year until the end of the lifetime T; and FLH denotes the full load hours the plant delivers in each operating year.

$$LCOE = \frac{C_0 + \sum_{t=1}^{T} \frac{C_t}{(1+CoC)^t}}{\sum_{t=1}^{T} \frac{FLH_t}{(1+CoC)^t}}. \tag{2}$$

Assuming constant FLH in each year, the derivative is formally presented in equation (3) and in a short form in equation (4).

$$\frac{\partial LCOE}{\partial CoC} = 0 + \frac{C_0}{FLH} + \frac{2C_0(1+CoC)}{FLH} + \frac{3C_0(1+CoC)^2}{FLH} + \cdots + \frac{TC_0(1+CoC)^{T-1}}{FLH}. \tag{3}$$

$$\frac{\partial LCOE}{\partial CoC} = \sum_{t=1}^{T} \frac{tC_0(1+CoC)^{t-1}}{FLH}. \tag{4}$$

As shown in the equations, the derivative is always positive because C_0, CoC, and FLH are positive by definition. The sensitivity of the LCOE to changes in the CoC depends on the relationship of initial investment costs C_0 with FLH and on the level of the CoC. Put differently, the higher the initial investment cost, the larger the effect of an increase in CoC on the LCOE. The higher the FLH, the smaller the effect of an increase in CoC on the LCOE because the asset is producing more for a given initial investment sum. Further, the higher the level of the CoC, the larger the effect of an increase in CoC on the LCOE, as the relation is non-linear. This last aspect already provides an important policy implication, namely, that de-risking RE investments and thereby decreasing the CoC is even more important in high-CoC environments. Figure 7 indicates these relations conceptually for low, medium, and high CoC. For all scenarios, the slope becomes steeper as the CoC increases. Higher OPEX only have a level effect, while higher CAPEX and higher FLH also change the slope of the curve.

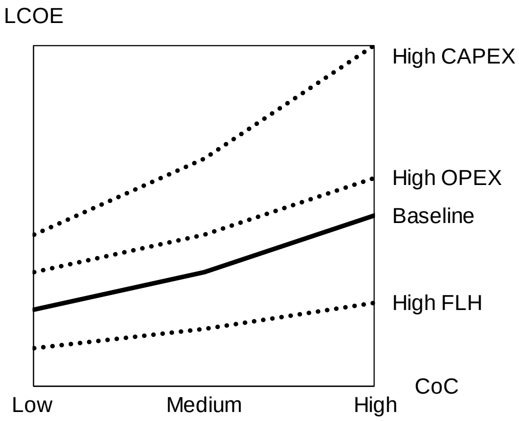

Figure 7: Relationship between cost of capital and LCOE. The figure depicts three ceteris paribus scenarios compared to the baseline: FLH double (high FLH), CAPEX double (high CAPEX), and OPEX double (high OPEX).

Moreover, financing conditions are of greater significance for RE compared to FFs for two reasons. First, RE faces higher CAPEX compared to FFs, thereby increasing the effect of the CoC on the LCOE. Second, RE faces physical constraints in the FLH (i.e. uncertainty of solar irradiation and wind availability), whereas FFs do not face these constraints. In reality, newly built RE often competes with existing FFs. In these cases, the marginal cost of FFs must be compared to the LCOE of RE (Schmidt et al., 2019), but the fact remains that the cost competitiveness of RE compared to FFs is hampered with the increase in the CoC (Hirth and Steckel, 2016; Schmidt, 2014). Figure 8 demonstrates that the initial investment and the capital service constitute merely approximately 15% for FFs but up to 91% for RE. The right-hand side of the figure indicates the implications of this with the example of solar PV. Increasing the assumed CoC from 4% to 12%, which is a common range for solar PV projects in countries of the European Union (eclareon and Fraunhofer ISI, 2019), yields financing costs (debt and equity) of over half the LCOE.

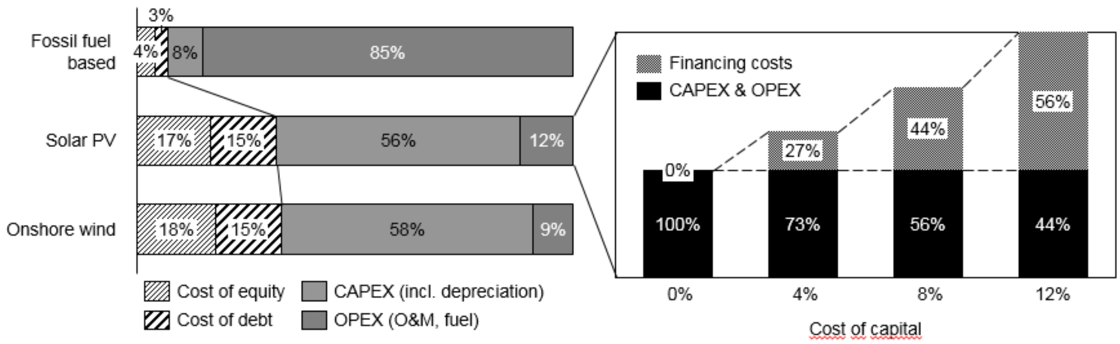

Figure 8: The technology-specific impact of the CoC. Left: Varying capital intensities for different electricity generation technologies (LCOE shares depicted). Right: Capital intensity for solar PV depending on the assumed cost of capital (LCOE shares depicted). Figure assumes 5% cost of debt and 10% cost of equity, European fuel costs—fossil fuel-based is

the average of hard coal, natural gas, and diesel. Numbers based on (Egli et al., 2018; Schmidt, 2014)*. Figure source*: Egli et al. (2020).

Consequently, high costs of capital are considered major obstacles to RE deployment (Creutzig et al., 2017; Shrimali et al., 2013). By the same logic, low costs of capital can contribute to cost reductions for RE (Bolinger and Wiser, 2012; Nemet, 2006; Trancik et al., 2015). Thus, financial markets play both a constraining or enabling role in the transition to low-carbon energy (Hall et al., 2017).

2.5 Public policy

While the challenge is evident and the role of finance established, it is not evident that policies must be used to redirect financial flows. This section provides rationales from different streams of literature for policy intervention and provides examples in the climate and energy policy domain (cf. Figure 2). Box 1 additionally provides examples of how two prominent policies relate to the rationales. Finally, I argue for a temporal rationale for policy intervention in the context of climate and RE finance.

Orthodox economics[10] suggests government interventions in the presence of market failures. Typically, market failures include negative (e.g. pollution) or positive externalities (e.g. no knowledge appropriability), the lack of competition (e.g. monopoly), and asymmetric information (e.g. adverse selection). A large body of economic literature demonstrates the case for government intervention in the presence of negative externalities (Varian, 2010). The most prominent example of a negative externality is that emitting carbon into the atmosphere is often free, although it creates a global cost. A CO_2 price is the classic optimal policy response (Nordhaus, 2019); however, research has shown the difficulty of implementation (Meckling et al., 2015; Pahle et al., 2018). Similarly, positive externalities are important in the fight against climate change. A typical positive externality is the fact that knowledge cannot remain in-house; hence, the incentive to innovate and produce new knowledge is below the social optimum because the innovator cannot reap the profits (Roper et al., 2013). Patenting is the classic policy approach to positive knowledge externalities. However, in the case of low-carbon innovation, where the policymaker is interested in rapid and widespread diffusion, patenting may not always be optimal, as it can create monopoly-like situations (Varian, 2010). Such monopolies are a source of welfare loss for consumers and overall deadweight loss (Varian, 2010). From an innovation perspective, the situation is less clear (Noharia and Gulati, 1996). On the one hand, less competitive markets enable companies to accrue greater profits, thereby

[10] 'Orthodoxy generally refers to what historians of economic thought have classified as the most recently dominant 'school of thought,' which today is "neoclassical economics." … In our view, neoclassical economics is an analysis that focuses on the optimizing behaviour of fully rational and well-informed individuals in a static context and the equilibria that result from that optimization.' (Colander et al., 2004). Following this definition, information asymmetries would typically not exist; however, as Colander et al. (2004) describe, the current 'elite' in economics has evolved from orthodox economics in various aspects and is rather open to new concepts. Information asymmetry is one of these concepts that is well established (see further in this section).

providing them the slack they need to finance high-risk innovative projects. On the other hand, stifled competition can also lead to lower incentives to innovate as market shares are not in danger. Finally, asymmetric information occurs in markets where buyers and sellers have access to different sets of information (Varian, 2010). In the context of this dissertation, this is most relevant in financial intermediation and discussed in section 2.1.

In addition, coordination failures, path dependencies, short-termism, risk aversion, and uncertainties may be present in the context of climate and RE finance, thereby providing further rationales for policy intervention. Innovation systems require the complex interplay of numerous actors. Initially, it is not always evident who can benefit to what extent; thus, there may be coordination failures (Cooper and John, 1988). Government policies—such as targeted low-carbon research programs, demonstration projects, and low-carbon innovation clusters—are exemplary policies to address this failure. Moreover, innovation studies indicate the importance of path dependencies (Dosi and Nelson, 1994). Firms and people are reluctant to deviate from what they have been doing in the past, although the choice of action in the past may have been almost accidental in the first place. Once taken, powerful increasing economies of scale lead to the dominance of a certain technology or process, which is difficult to challenge (Arthur, 1989). Such dynamics are at play in numerous markets, including RE finance (Hall et al., 2017). The presence of path dependencies and corresponding technology lock-outs justifies policies beyond carbon pricing (Neuhoff, 2005), which are even recognised by formerly pronounced 'carbon price only' advocates as a measure of last resort (Nordhaus, 2019).

Moreover, financial markets suffer from short-termism (Haldane, 2015). For example, the tradition of reporting quarterly earnings and profits leads to investment decisions that are tailored to short-term success instead of long-term sustainability. This is particularly concerning in the case of climate change, where there are numerous negative impacts in the future. Further, risk aversion and the presence of large uncertainties can lead to private investment levels that are below the social optimum (Mazzucato and MacFarlane, 2019; Mazzucato and Semieniuk, 2017). As transitions involve a substantial number of uncertainties and high-risk novel technologies and projects, policies can help to alleviate risks initially and pave the way for private investment (Geddes et al., 2018; Mazzucato and Penna, 2016).

Box 1: How State Investmetn Banks (SIB) and Feed-in Tariffs (FIT) address RE deployment barriers

Papers 3 and 4 refer to the role of SIBs and paper 2 analyses the effectiveness of FITs. Research has identified five key roles of SIBs: capital provision, de-risking, education, signalling, and first or early movers (Geddes et al., 2018; Steffen et al., forthcoming). FITs enable technology-specific support and guarantee project cash flows, thereby reducing investment risk. Empirically, they were successful in inducing RE deployment if they were credible, did not change frequently (Nemet et al., 2017; Wiser and Pickle, 1998), and took the form of 'strategic deployment', which enabled industry experimentation, learning, and eventually economies of scale (Nemet et al., 2018; Neuhoff, 2005). For each barrier, I discuss how SIBs and FITs can address them.

First, SIBs and FITs indirectly address negative externalities because both policies can be technology-specific and, therefore, enable low-carbon technologies to compete with carbon-intensive technologies emitting carbon at zero cost. Second, positive externalities are addressed to a lesser extent with these two policies. By subsidising demonstration projects, SIBs can, for example, alleviate the issue. Third, both policies alleviate concerns regarding low competition in the energy sector by providing a market for excessively expensive novel technologies and facilitating market entry for newcomers. Fourth, SIBs particularly address information asymmetry between investors and project developers: Through their educational role, SIBs provide tools and standards for risk assessments or financing deal structures (Geddes et al., 2018). Fifth, SIBs reduce coordination failures by launching new projects with a variety of partners (e.g. from law firms to project developers) and building a trusted investment ecosystem, which reduces investment risk (cf. section 4.4). Sixth, SIBs and FITs help to break path dependencies. SIBs are often early movers into new technologies and asset classes, thereby breaking path dependencies and enabling investors to build up a track record, data, and experience. In turn, this track record drives down financing costs (cf. section 4.3). FITs have proven their effectiveness in enabling novel technologies to travel down a cost learning curve, thereby breaking up the technology lock-in (Nemet, 2006; Polzin et al., 2015; Rubin et al., 2015). Seventh, SIBs can address short-termism in financial markets by providing strategic long-term public capital in their capital provision role (Geddes et al., 2018). Eighth, SIBs address risk aversion by de-risking projects (e.g. via guarantees) and using their reputation to signal the soundness of novel projects. For example, in numerous cases, an initial commitment of an SIB suffices to crowd-in private investment without a direct SIB investment (Geddes et al., 2018). By definition, FITs also de-risk projects. In addition, FITs helped reduce financing costs for RE substantially by reducing investment risk, which may contribute to the overall decrease in RE cost (cf. sections 4.2 and 4.3; May and Neuhoff, 2017).

Further, in the context of climate and RE finance, policy intervention is urgent and timely. First, it is urgent because pathways to a climate consistent with the Paris Agreement ‘are rapidly narrowing’ (Lamontagne et al., 2019). As the current emission gap reveals, there is likely too little policy intervention for markets to steer into a climate-safe future. Second, it is timely because the rapid cost decreases of RE along with the loss of market value and power of fossil fuel companies may create a dynamic where low-carbon assets become the new norm. Simultaneously, financial markets are beginning to price climate risks (cf. section 1.1) and favour climate-saving investments. In a recent survey among researchers, these technology cost dynamics and financial markets were identified as two of six social tipping points for climate action (Otto et al., 2020), and policy intervention may be particularly impactful close to such tipping points, which trigger self-reinforcing dynamics (Farmer et al., 2019).

Given the diversity of rationales for policy intervention, the urgency and the potential window of opportunity, this dissertation examines a broad set of policy interventions that are aimed at leveraging the potential of finance to accelerate the decarbonisation of economies in the fight against climate change.

3 Methods

This dissertation employs both non-empirical and empirical approaches. All methods are discussed in detail in the respective sections of the papers in Annex I. The non-empirical methods include a conceptual paper, a semi-structured literature review, and a model-based paper. The empirical approaches, which form the core of the dissertation, include quantitative descriptive and regression analysis and qualitative interview analyses. Most papers combine several approaches in a mixed methods approach.

3.1 Non-empirical approaches

Paper 1 is mainly conceptual; Paper 2 is a literature review, considered non-empirical (Dan, 2017); and Paper 5 is a model-based paper. Paper 1 develops a novel mechanism to assign climate finance responsibility among the parties to the Paris Agreement. A conceptual approach is appropriate, because there is little research offering guidance on how to allocate climate finance responsibility. Current approaches either encompass a small set of countries (Pickering et al., 2015) or are based on existing international donor schemes unspecific to climate change, such as the United Nations (UN) (Cui and Huang, 2018). The two-pillar mechanism is based on emission responsibility and ability to pay. We compile publicly available data on GHG emissions, GDP, unconditional GHG reduction commitments in NDCs, and climate vulnerability for 164 countries. Applying the developed mechanism, these data are used to calculate annual climate finance responsibility for each country in various specifications.

Paper 2 conducts a systematic review of the peer-reviewed empirical literature on the effectiveness of renewable energy policy to mobilise private RE investment. By considering policy designs, it allows for a more granular analysis of policy effectiveness in relation to the rationales for intervention (cf. section 2.5) compared to most papers. The paper employs a semi-structured method, commonly used in the social sciences, to assemble the literature base (Auld et al., 2014). It provides a more transparent, reliable, and replicable means of selecting literature as compared to the classical narrative review (Hart, 1998), while being less structured and more flexible than a meta-analysis (Hunter and Schmidt, 2004). The flexibility enables an adequate consideration of qualitative evidence, which is key to understanding policy design.

Paper 5 is a response to an energy system model publication (Bogdanov et al., 2019), which modelled 100% RE worldwide. It uses publicly available data (Damodaran, 2019) and builds on Egli et al. (2018) to develop country-specific costs of capital for solar PV investments. The failure to account for country differences by using quasi-uniform CoC in energy system models—such as state-of-the-art models from the IEA, the IRENA, or extant literature—may produce biased policy implications (Egli et al., 2019). To correct for this, we use the model inputs from Bogdanov et al. (2019) to feed a basic LCOE model for six countries (see equation (2)). The LCOE model is identical to that of Egli et al. (2018) and is used to calculate three different cost of capital scenarios, which are then compared with one another.

3.2 Empirical approaches

Papers 3 and 4 utilise data that was elicited in direct contact with RE investors. Both papers focus on onshore wind and solar PV and the former is limited to Germany while the latter analyses Germany, Italy, and the United Kingdom. On the one hand, the papers utilise (quantitative) project-specific financing condition data; on the other hand, the papers utilise (qualitative) coded interview data on mechanisms and drivers of change. Paper 3 also employs a simple LCOE model following equation (2) and develops an approach to attribute changes in LCOE to changes in financing costs and specifically to disentangle experience effects from general interest rate effects (see Annex I for details).

Paper 3 uses the elicited financing data to reveal the evolution of the CoC using equation (1). Moreover, the paper transfers the concept of experience curves from technology cost to financing cost, thereby testing an evolutionary lens on RE finance (cf. section 2.2). We use three common financial indicators for RE projects and investigate whether there are experience effects using a one-factor experience curve, following Wright’s law (Wright, 1936). We select cumulative global investment as the independent variable based on exploratory investor interviews, which indicate that the financing of large project finance deals is international and increasingly global. Finally, we apply a series of robustness checks by utilising different specifications of the dependent variable and employing investor fixed effects. The former is employed for concerns regarding the relevant geographical scope to accumulate experience changes (Huenteler et al., 2016), which affects the empirical identification of experience rates (Lindman and Söderholm, 2012), and the latter is employed to account for investor heterogeneity (projects were made comparable by specifying a reference project[11]).

While Paper 4 also utilises financing data, it uses coded interview data to link changes in RE investment risk to underlying drivers. Qualitative methods are suited to understand FI behaviour (cf. section 2.1) and path dependent decision making in particular (cf. section 2.2). Methodologically, the paper employs three main approaches: a literature review, risk rankings, and a network analysis of investor interviews. Moreover, it also reports financing data based on reported project finance conditions, similar to Paper 3. In the first step, I present a semi-structured literature review with a replicable search string to define the scope of papers and qualitative abstract screening to identify relevant papers. This is a suitable approach to develop an understanding of the most important RE investment risk types. In the second step, I utilises

[11] The reference project specifies an investment sum of approximately €20 million and standard established technology, which ensures that the sources of finance are established debt and equity investors (e.g., excluding early stage debt or venture capital).

risk rankings from investor interviews at three points in time, evoking an anchoring event to avoid retroactive sense-making biases (Choi and Pak, 2005). In the third step, I utilise a network analysis of the interview transcripts to identify the drivers of changes in investment risk. The interviews were open, with little structure except for the defined risk types, which enables the collection of rich and complex data (Eisenhardt and Graebner, 2007). The transcripts were then coded using the software MaxQDA and the coder developed risk drivers iteratively to best fit the interview statements. In grounded theory, this procedure is termed 'open coding', an approach which is useful to develop categories by comparing coded statements and identifying common patterns (Walker and Myrick, 2006). In order to illustrate linkages between the evolution of the relative importance of risk types (i.e. ranking) and risk drivers, I use the co-occurrence of the risk types and the resulting driver categories.

4 Summary of results

4.1 A dynamic climate finance allocation mechanism reflecting the Paris Agreement (Paper 1)

This paper examines the responsibilities of countries to provide climate finance, a climate policy tool, as described in Figure 2. Achieving the NDCs requires substantial climate finance efforts (cf. section 1.1). The associated problem is threefold: First, the contributing parties have no guidance to determine their fair share; thus, the civil society has no tools to evaluate contributions. Second, the 2018 UNFCCC (COP24) in Katowice introduced biennial ex-ante communications of climate finance contributions from 2020 onwards (UNFCCC, 2018a), thereby reinforcing the need for guidance. Third, the COP24 opened deliberations on a new climate finance target (likely post-2025) (UNFCCC, 2018b), thereby reflecting the fact that the currently committed USD 100 billion p.a. is likely insufficient to achieve the goal of the Paris Agreement (Peake and Ekins, 2017) let alone achieve sustainable development goals (McCollum et al., 2018). Such a new target may appear possible with a broader scope of contributing parties (cf. Art. 9, Paris Agreement).

Here, we develop a novel climate finance allocation mechanism (illustrated in Figure 9) to provide a benchmarking tool. The mechanism embodies the key principles of the Paris Agreement. First, it reflects the principle of common but differentiated responsibilities in providing flexibility regarding the scope of contributors and in accounting for expected future climate damages. Second, it introduces a dynamic forward-looking component that rewards increasing ambition over time (ratcheting up), which is similar to policy sequencing to increase stringency over time (Pahle et al., 2018). Thus, if a country exceeds the average level of ambition, it can thereby reduce its climate finance contribution. We run the mechanism on two scopes: 1) A Cancun scope encompassing 49 developed countries and reflecting the current commitment; and 2) a Paris scope encompassing 164 countries, representing all signatories except least-developed countries with emissions consistent with the Paris Agreement carbon budget (see Annex I for details).

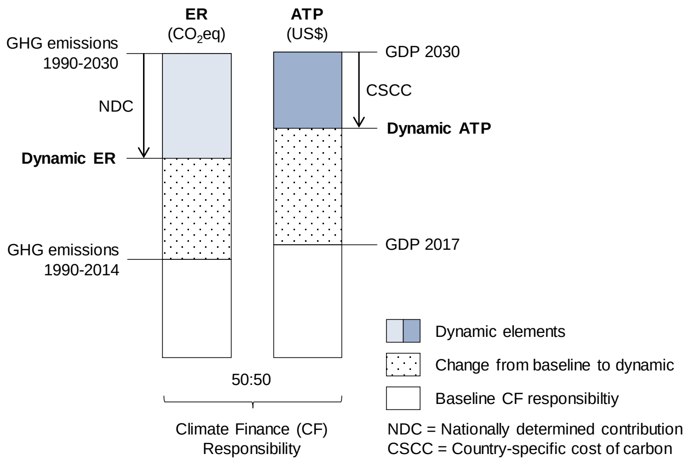

Figure 9: Climate finance mechanisms (Egli and Stünzi, 2019).

In order to illustrate the effect of dynamic elements, Figure 10 depicts that for Russia and the US, the inclusion of dynamic elements has opposing effects depending on the scope. There are two reasons for this. First, compared to the average developed country, these countries have unambitious emission reduction targets. However, when compared to emission-intensive economies on a growth path, like India for example, their expected emissions are lower. Second, the Paris scope includes emerging economies that typically grow faster than developed economies. Hence, the share of developed countries in world GDP decreases over time in the Paris scope, thereby reducing their future ATP (in relative terms).

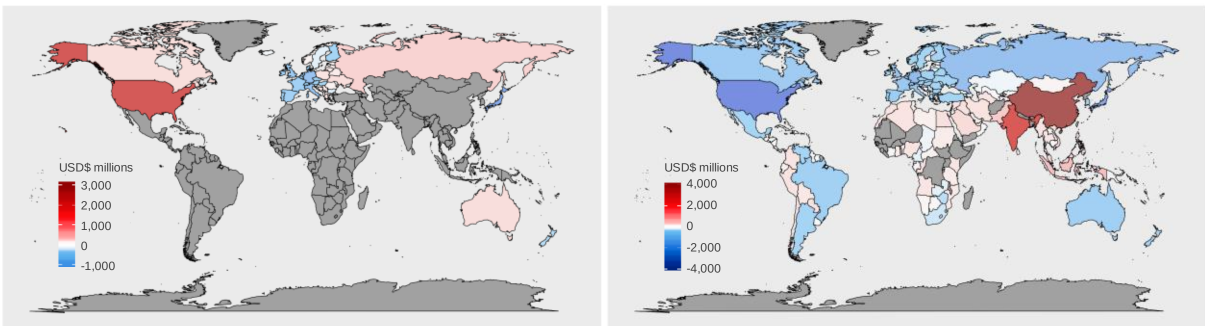

Figure 10: Change in climate finance responsibilities from baseline to dynamic mechanism for Cancun (until 2025) and Paris (post 2025) scopes in USD million (Egli and Stünzi, 2019).

This analysis reveals four key insights. First, there is a large heterogeneity regarding the alignment of pledges with responsibilities. A few European countries, such as Germany and France, pledged above their responsibility. Others, such as the US or Switzerland, would need to increase their pledges substantially—for example, the US eighteen-fold in the Cancun scope. Hence, in order to legitimise a discussion on post-2025 contributions of all parties, current climate finance efforts of developed countries may need to step up. Second, if such a discussion were to take place, countries currently claiming financial support to achieve their NDCs may actually need to contribute to climate finance instead (e.g. Pakistan). Third, the mechanism provides an incentive to peer-review the implementation of NDCs, in line with insights regarding policy surveillance (Aldy, 2017). Countries that implement their NDCs and incur related costs will want to ensure that other countries follow up on their commitments so that they avoid overpaying within the climate finance mechanism. In the absence of an international body with oversight and sanctioning capacity, increasing incentives for undertaking peer-reviews of NDCs will be crucial to achieve substantial emission mitigation. Fourth and last, the analysis reveals that conventionally excluded 'bunker fuels' from international aviation and shipping would result in a substantial climate finance responsibility. Together, these sectors would be required to contribute USD 3.3 billion annually, placing both among the top 20 contributors.

4.2 How do policies mobilize private finance for renewable energy?—A systematic review with an investor perspective (Paper 2)

This paper reviews the empirical evidence on the effectiveness of energy policies to induce private RE investment (cf. Figure 2). Its aim is to verify empirically, which of the many policy instruments that can be used to respond to the rationales for intervention (see section 2.5) work empirically. Based on a semi-structured method (see Annex I for details), we selected 96 peer-reviewed empirical studies that analyse policy effectiveness in investment grade countries including Brazil, South Africa, India, and China. Figure 11 illustrates that most studies are either single-country case studies or large-n analyses. Most of the large-n and some of the small-n analyses employ regression techniques and the majority of studies is quantitative, but qualitative analyses are also frequent (about one-third of the total).

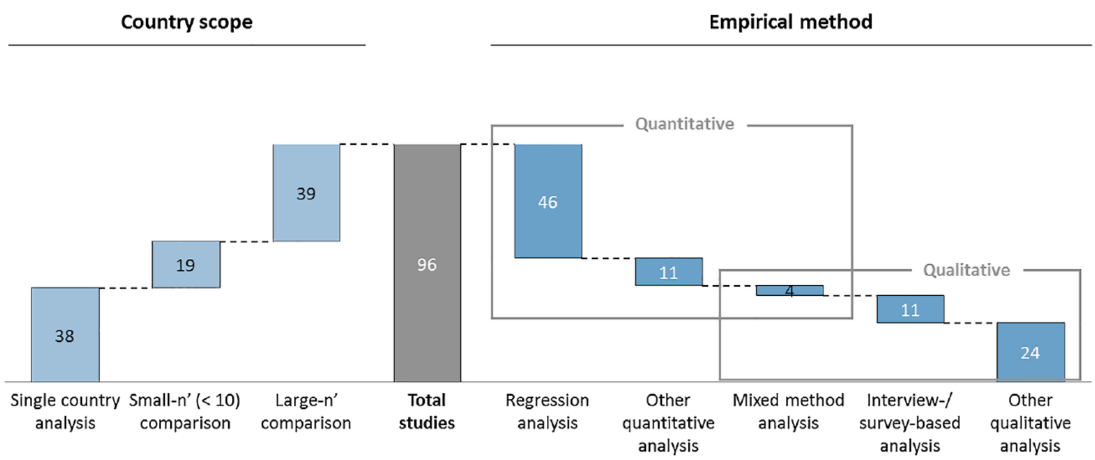

Figure 11: Geographical and empirical scope of the reviewed literature (Polzin et al., 2019).

Conceptually, we employ the framework in Figure 12 to analyse policy effectiveness. Financial literature has long established a positive relationship between investment risk and return in theory (Merton, 1973) and, more recently, empirically (Ghysels et al., 2005; Lundblad, 2007). Particularly in project-finance setups, which are specifically important for RE investments, higher project risks translate directly into higher required returns (Kitzing and Weber, 2015), because the only collateral available to financiers is the RE asset and its expected future cash flows (Yescombe, 2013). For example, in order to make investment A viable in Figure 12, a policy has three possible levers: change the risk profile of the investment opportunity (1), change the return profile (3), or affect a combination of both (2, 4) (cf. Dinica, 2006; Waissbein et al., 2013). Depending on the de-risking of a policy, the required additional return to reach the market line changes. For example, a fixed FIT eliminates market risk and hence requires a lower return premium compared to a policy that only reduces market risk (e.g. RPS). Moreover, as the dashed arrow (4) shows, policies can also increase risk if the policymaker and/or the setup of the policy suffers from a lack of credibility that outweighs the addressed risks (e.g. market risk). In analysing these levers, we emphasise the importance of policy design in addition to the policy instrument (Schmidt and Sewerin, 2019). For example, the effectiveness of RE auctions will crucially depend on the auction design that includes contract duration, pricing, process, and other factors.

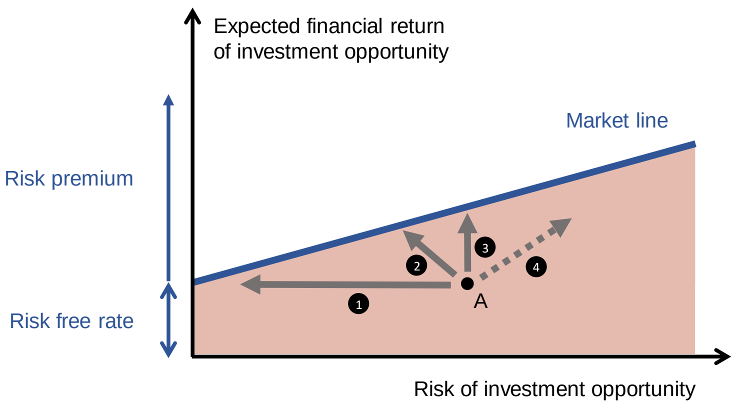

Figure 12: Conceptual risk-return framework with policy impact based on Polzin et al. (2019)

Policies are classified by utilizing a simplified version of the IEA and the classification of IRENA Policies and Measures (OECD/IEA and IRENA, 2018) and provide a detailed analysis of the policy design features of FIT, auctions, and RPS—the three most frequently implemented and analysed policy instruments. Overall, it is found that FIT (also in the early stages of the technology lifecycle), RPS/quota mechanisms, and auctions (particularly for mature technologies) tend to be effective instruments when used along with a credible RE planning framework, particularly in comparison to other fiscal/financial, regulatory, or market-based instrument types, like green certificates. However, corresponding with theory, the analysis reveals that identical instrument types can produce rather diverse results. One level of granularity deeper, the literature generically suggests that high policy stringency (Carley et al., 2018; Shrimali and Jenner, 2013) and predictability both increase policy effectiveness (Eleftheriadis and Anagnostopoulou, 2015). For example, retroactive policy changes reduce effectiveness: RPS policies had a smaller effect in states which previously passed and repealed electric utility industry restructuring legislation (Fabrizio, 2013). However, iterative forward policy adaptation, building on learnings from past policies, and following market development keeps policy costs down (Surana and Anadon, 2015). In this regard, continuous monitoring, evaluation, and coordination among government bodies increase policy credibility and reduce legal risk, thereby satisfying investors' needs (Holburn, 2012; Nemet et al., 2017).

The review of specific policy design options of FIT, auctions and RPS reveals the fundamental trade-off between technology specificity and neutrality. While the former increases technology diversity and dynamic efficiency (e.g. pulling a technology down its learning curve), it also increases policy cost. If deployment/volume caps are introduced to ensure policy costs remain manageable, mechanisms and lead times must be transparently communicated to avoid negative effects on projected returns and calculated risks. Above all, standardized procedures and common design elements of policy instruments enable investors to gain experience more quickly and, consequently, reduce the risk of RE projects.

4.3 A dynamic analysis of financing conditions for renewable energy technologies (Paper 3)

This paper utilises novel data on financing conditions for onshore wind and solar PV projects in Germany from 2000 to 2017 in order to develop a better understanding of RE finance and quantify changes over time (cf. Figure 2). These two technologies are the most deployed non-hydro RE and Germany was one of the earliest markets. The sample begins when Germany introduced its framework RE support policy (EEG) (Jacobsson and Lauber, 2006). The German electricity market has been liberalised since 1998 (Jacobsson and Lauber, 2006) and the vast majority of investment in RE has been private (Trend Research, 2013). We restrict the analysis to utility-scale project finance (i.e. downstream, see section 2.3), which is the structure used for 96% of large solar PV projects and 88% of large wind onshore projects between 2000 and 2015 (Steffen, 2018).

The analysis proceeds in four steps. After compiling a novel data set on financing conditions for 133 utility scale projects, step one involves the evolution of the CoC (Figure 13) and additional financial indicators, such as the debt margin and the loan tenor or the DSCR (see section 2.4). Large changes over time are revealed and it is found that the CoC declined by 69% for solar PV and by 58% for onshore wind onshore projects between the early period of the RE finance industry (2000–2005) and 2017. Similarly, there are decreases in debt margins, increases in loan tenors and decreases in the DSCR—all of which indicate more favourable financing conditions over time.

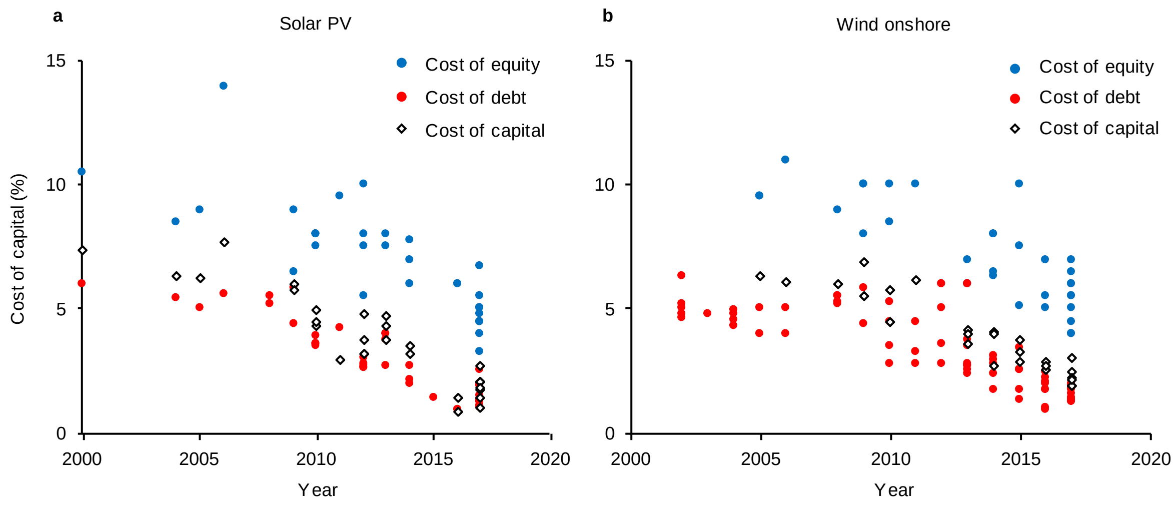

Figure 13: Cost of capital, cost of debt, and cost of equity for all 133 RE projects (Egli et al., 2018)*.*

In the second step, insights from 41 qualitative RE investor interviews are utilised to identify drivers for change on three levels: the economy, the renewable energy sector, and the renewable energy finance industry. Drivers linked to the first level include changes in the general interest rate and the abundance of liquidity in capital markets, thereby indicating the importance of other policies, such as monetary policy (cf. Figure 2). Drivers linked to the second level include performance data, technology reliability and the RE regulatory environment. Drivers linked to the third level include learning among investors, better risk assessment tools, standardised contracts, or tougher competition. The third level indicates the importance of adaptive market behaviour (cf. section 2.2), as the RE finance market is shaped by path dependencies and learning.

In the third step, the contributions of these levels are quantified. Specifically, the first level is controlled for by netting out general interest rate changes (cf. Figure 2) and the combined effect of the second and third levels is quantified by calculating experience rates (see Annex I for details). In the preferred specification, an experience rate of 11% is found for debt margins. In other words, for every doubling of global cumulative investment, the debt margin decreases by 11% for both technologies. Further, experience rates of 13% are found for the DSCR of solar PV projects and of 17% for the DSCR of onshore wind projects. With regard to loan tenors, an experience rate of -3% is found—that is, increasing loan tenors with increasing experience (statistically insignificant for onshore wind). In sum, substantial experience effects on several RE financing indicators are found using standard one factor experience curves. After the qualitative evidence for the importance of adaptive market behaviour, this step adds quantitative evidence to an RE finance experience effect.

Finally, in the fourth step, the debt margin is used to compare the experience effect with the overall decline in the general interest rate and establish the effect on LCOE of both technologies from 2000 to 2017. Over this period, 10-year German government bond yields declined from 5.3% to 0.3%. Using the estimated experience curve, debt margins declined 1% point for onshore wind and 1.5% points for solar PV. For comparison, this decrease corresponds to a change in the corporate ratings of a financial service firm from BBB to AAA for onshore wind or from B+ to AAA for solar PV. Using a straightforward approach (see Annex I for equations), the effect of changing financing costs on the LCOE is singled-out (40% of total reduction). Our findings suggest that the experience effect contributed 1%–4% (solar PV and onshore wind respectively) to LCOE reductions and the general interest rate contributed 4%–20%.

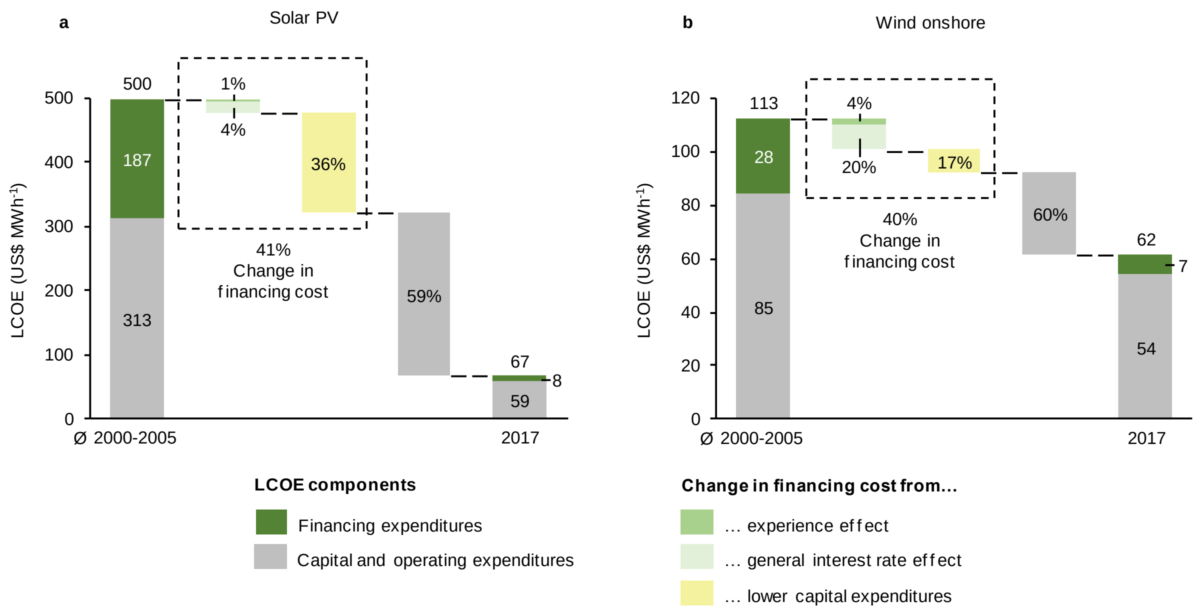

Figure 14: LCOE changes for both technologies assigned to different components with a breakdown of effects contributing to financing costs.

For onshore wind, CAPEX remained relatively constant over the period of study, increasing the relative importance of the general interest rate and experience effects. As both technologies become mature, the relative importance of these effects is likely to increase.

4.4 Renewable energy investment risk: An investigation of changes over time and the underlying drivers (Paper 4)

In this paper, I build on Paper 3 to develop a better understanding of the relationship between changing financing conditions and underlying RE investment risk and hence FI behaviour (cf. Figure 2 and section 2.1). Further, I use qualitative evidence from coded interviews with 40 investors to identify risk drivers. I analyse RE investment risk for onshore wind and solar PV in Germany, Italy, and the UK at three points in time: 2009, 2013, and 2017. The selection of years was motivated by three reasons. First, the lion's share of investments and capacity deployments happened from 2009 onwards. Second, I chose to elicit data at three points in time with equal intervals in order to infer dynamics over time. Third, by beginning in 2009, I circumvented the 2007–08 financial crisis and cover a period of relatively stable interest rates.

The study proceeds in three steps. First, I conducted a literature review and used exploratory interviews to identify the most important RE investment risk types, which are presented in Figure 15. Figure 15 also displays the results of step two, where I asked investors to rank risk types in each year. Technology and policy risks declined the most, while price and curtailment risks increased the most and resource risk remained approximately constant (all in relative terms). Overall, RE investment risk declined substantially as well, as confirmed by investors (see Annex I for details) and financial indicators, such as debt margins, DSCR, leverage, and loan tenors. Apart from the aggregate changes, I show that curtailment, policy, and price risks vary by country, while resource and technology risks vary by technology. For example, policy risk peaked in 2013 in Italy due to looming concerns regarding retroactive policy changes and remained high in 2017, whereas the risk was the least important in Germany in 2017.

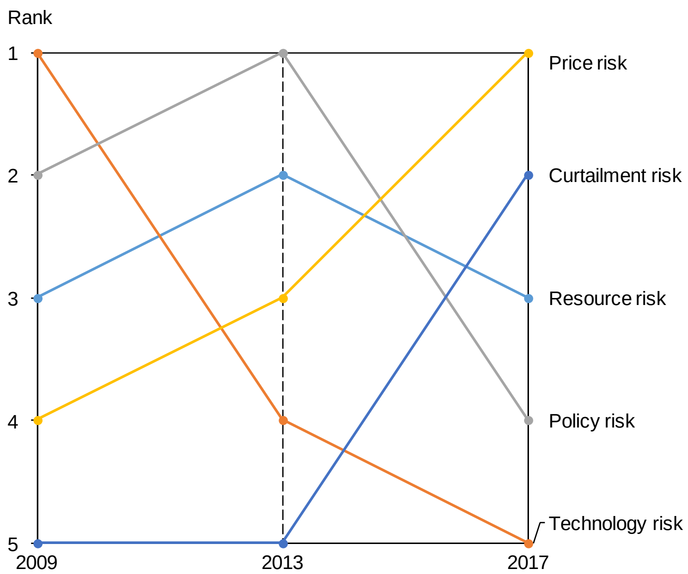

Figure 15: Evolution of the five most important RE risk types for onshore wind and solar PV in Germany, Italy, and the UK (Egli, 2020). *See paper in Annex I for definitions of risk type.*

In the third step, I used a network analysis of the 869 coded statements in the interview transcripts to identify the drivers of investment risk changes. Figure 16 illustrates the co-occurrences of risk types and drivers (see Annex I for detailed results including sub-drivers). The main driver of curtailment risk is policy credibility and setup, which determines, for example, whether RE generation can be fed into the grid with priority over other sources and whether curtailment will be compensated. Policy risk is mainly driven by credibility, which is why it decreased in Germany relative to the other risks and increased in Italy. However, other factors also contributed to this. For example, investors understood policymakers better over time, thereby making future policy more predictable. As one investor put it, 'There is regulatory learning. You understand the regulator better […]'. Price risk was driven by the move towards more market-based RE policies, including wholesale price exposure or premium auctions. For an investor, these policies introduce volatility in future cash flows and, therefore, increase risk margins (cf. Pahle and Schweizerhof, 2016). As one investor explained, 'you calculate project [revenues] over a long time, while you fully look into a black box regarding the future price [of electricity]'.

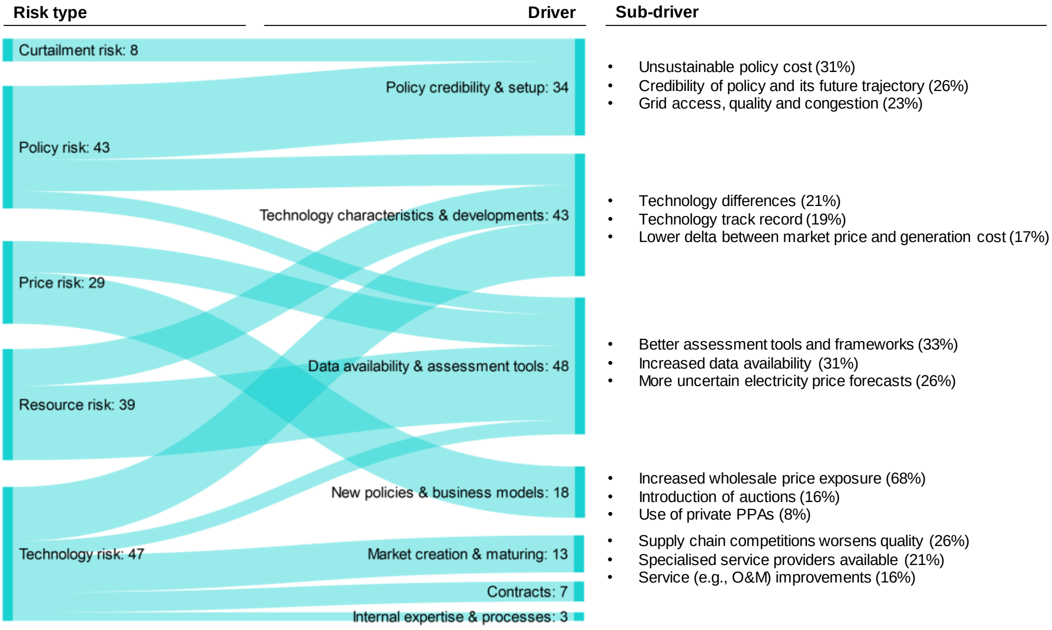

Figure 16: Drivers for each risk type from coded interviews with 40 RE investors (Egli, 2020). *Sub-drivers are indicated for drivers with more than 10 co-occurrences. Note that one coded statement can involve several risk types and drivers.*

Resource risk mainly differed among technologies because wind predictions are less precise than solar irradiation predictions. Finally, a successful technology track record (including data availability) is the main prerequisite for a lower technology risk. As one investor explained, 'We just saw that the first parks going into operation in Germany around 2005 and 2006 ran consistently without problems for around eight years'.

4.5 Bias in energy system models with uniform cost of capital assumption (Paper 5)

This paper is a 'Matters Arising' response to Bogdanov et al. (2019), which evaluates the feasibility of a 100% renewable energy system for 145 global sub-regions. Specifically, we point out the need for country-specific CoC in energy system models, which produce country-specific results due to the high sensitivity of the LCOE to CoC changes as describes in section 2.4. Therefore, in this contribution, we put the observed variation and dynamics of RE financing conditions in a bigger picture by considering its effect on model results. We show that there is a large variation in CoC across countries. Figure 17a depicts the estimated solar PV CoC for 152 countries. We use the 10-year average solar PV CoC for Germany as a baseline (Egli et al., 2018) and add a country premium based on Moody's sovereign rating on top.

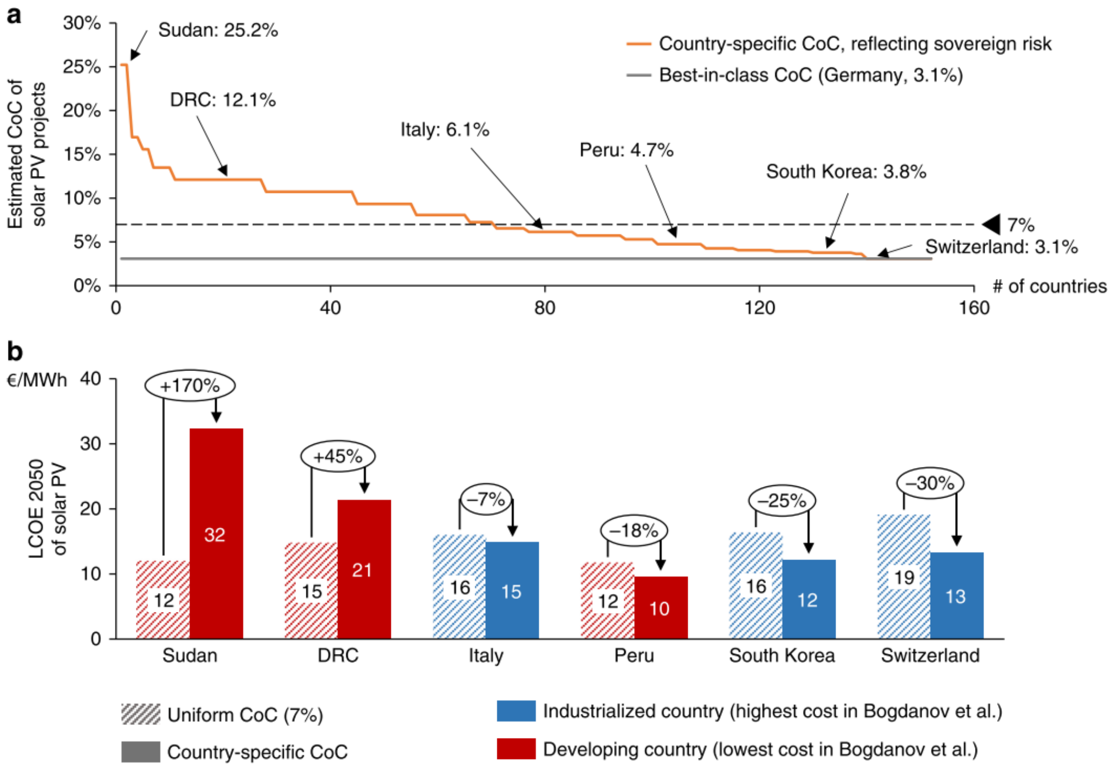

Figure 17: Estimated solar PV CoC for 152 countries worldwide (a) and solar PV LCOE for the three countries with the largest positive and the three countries with the largest negative change compared to baseline (Egli et al., 2019).

Panel b of Figure 17 contrasts the solar PV LCOE with uniform versus country-specific CoC for the three cheapest and the three most expensive solar PV-based RE systems according to the model (Bogdanov et al., 2019). Effectively, the results flip when new CoC is used, with industrialised countries showing lower solar PV LCOE than developing countries. Hence, using uniform CoC may underestimate the cost of RE in developing countries and overestimate it in industrialised countries. Even when assuming a halved spread between Germany and developing countries, the differences remain stark (+64% for Sudan, +5% for DRC).

5 Conclusion

5.1 Contribution to extant literature

The contributions of this dissertation to extant literature can be categorised into four parts: theoretical, empirical, conceptual, and organisational; the main contribution is in the empirical part.

First, this dissertation suggests the use of different theories to explain RE finance markets. The evidence in the dissertation suggests that efficient market hypotheses are a good starting point to understand RE finance; however, certain features of the adaptive market hypothesis help to comprehend RE finance more comprehensively. Papers 3 and 4 identify factors such as technology track record, performance data availability, assessment tools, investment ecosystem effects, and learning by doing as drivers that influence RE investment risk and financing conditions. While some of these factors are in line with efficient market behaviour in a market where new (RE) technologies are not yet competitive, this dissertation provides ample evidence that in numerous cases, financing barriers remain even though a technology is mature. The fact that technological maturity and ‘financial maturity’ do not coincide is interesting for policymakers. Further, adaptive market behaviour, governed by path dependency, may play a larger role in RE investment decisions than previously assumed. Importantly, adaptive market behaviour occurs at the investment ecosystem level and not only at the investor level. This dissertation reveals, for example, the importance of trusted partners, standardised contracts, and competition in providing low-cost RE financing. Hence, learning and adaptive market behaviour is a process that must be understood as part of the interaction of different actors in RE finance.

Second, this dissertation provides empirical evidence of the level of financing conditions, the dynamics of financing conditions, RE investment risk, and the drivers of change. The first empirical contribution lies in the identification of relevant financial indicators that could proxy investment risk apart from the CoC (e.g. debt margin, debt service coverage ratio, leverage or loan tenor) and the identification of relevant RE investment risk types. This paves a way for future research to focus on the relevant indicators, and the empirical elicitation of current and historical values for these indicators enables benchmarking in the future. For example, the indicators can be collected over time across countries and technologies (e.g. with potentially different maturity levels) to improve our understanding of RE financing conditions. The second empirical contribution lies in demonstrating that financing conditions are not static and in quantifying the change. This dissertation shows that these changes can have a major impact on the LCOEs of RE (Paper 3), modelling outputs (Paper 5), and, hence, policy implications. The third empirical contribution lies in the identification of drivers that are conducive to improving RE financing conditions and reducing RE investment risk. Financing conditions are influenced by the general macroeconomic environment and experience processes. The former is at the core of numerous economic analyses; however, it is rarely taken into account in academic and policy discussions around RE support schemes (Schmidt et al., 2019). The latter is even more absent, as mainstream theories—like the efficient market hypothesis—would question the importance of experience effects. Beyond macroeconomic conditions and experiences, this dissertation provides granular evidence on the drivers of different RE investment risk types, such as the interplay between technology cost and policy risk.

Third, this dissertation makes a conceptual contribution. Climate and RE finance are often analysed without considering political feasibility and political feedback effects (cf. Figure 2). However, governments and, hence, political entities must contribute to climate finance (Paper 1) and enact policies to spur private RE investment, thereby being consistent with the goals of the Paris Agreement (Paper 2). With regard to the first aspect, this dissertation develops a climate finance allocation mechanism that provides an incentive to peer-review the implementation of NDCs, in line with insights regarding policy surveillance (Aldy, 2017). As the provision of GHG emission mitigation is a public good (cf. section 2.5) and there is an incentive for governments to procrastinate climate action (Bernauer, 2013), there is a need for incentive-compatible policy design. Moreover, the mechanism provides the civil society with a tool to check the adequacy of a governments' climate finance contribution. Such reviewing and subsequent naming and shaming can be important to ensure more effective international collaboration (Kelley and Simmons, 2015). With regard to the second aspect, this dissertation alludes to the importance of feedback effects from RE finance on the political process. For example, decreasing RE financing costs lower the cost for RE support schemes (see Papers 3 and 4) and build up interest groups in the financial and the legal domain that push for a strong RE sector. The resulting dynamics are discussed as an avenue for further research.

Fourth, this paper makes an organisational contribution. If RE finance is partially governed by adaptive market behaviour, RE financing conditions are dynamic, and the interaction between politics, policies, and RE finance are crucial, there is a need to represent these complex interactions in models and policy analyses. Representing these interactions requires collaborations across disciplines. The resulting policy insights can become more relevant only if finance scholars are willing to work on questions without large-n datasets, if social scientists are willing to simplify their insights to a degree that makes model implementation possible, and if modellers agree to represent more complex and challenging socio-economic factors. With regard to modelling, Paper 5 indicates that more accurate depictions of CoC can already change model outputs substantially. Ongoing efforts to add socio-economic pathways to models (Bauer et al., 2017) and relate them to factors influencing financing conditions, such as the quality of governance, are much needed (Andrijevic et al., 2019).

5.2 Insights for policymakers

The findings of this dissertation suggest that there is great potential in considering finance more explicitly in the design and implementation of decarbonisation and renewable energy policies. Here, I first propose ways to integrate finance into energy policy; second, I offer general insights on policy design; and, third, I propose further thoughts that go beyond the findings of this dissertation and, finally, I provide avenues for further research.

Integrating finance into energy policy

The findings of this dissertation show that RE financing conditions are dynamic and depend, to a certain extent, on policy. Consequently, there may be a hidden co-benefit to deployment policies. Policies reducing risk tend to be most effective in attracting RE investment (Paper 2) and deployment policies with guaranteed remuneration are a key contributor to lowering financing costs for RE (Paper 3). Lower financing costs in turn lower LCOEs and, therefore, accelerate deployment. In order to tap into these mutually reinforcing benefits, policymakers must consider design elements beyond the choice of policy instruments with a particular focus on enabling RE investors to gain experience.

In order to do so, policymakers must consult with investors prior to policy enactment and ensure that the design considers the risk-return perspective. The findings of this dissertation indicate the importance of sharing data and expertise in order to develop credible and accurate financial and technical models (Paper 4). As a technology's track record and the credibility of assessment models are crucial to investors, policymakers must create open data sharing platforms for technical and financial indicators in order to accelerate the spillovers across different actors in the financial industry and the progress towards larger investors, as described in Figure 4. Widespread data and model availability additionally facilitate entry for new firms, create a market and a trusted ecosystem, and enable a high degree of competition. Competition can additionally be encouraged by crowding-in capital from a diverse set of investors. These are all factors that are conducive to improving the financing conditions for RE.

Various policy instruments can be used to achieve these goals. The findings of this dissertation indicate that all of the most frequently used policy instruments (auctions, FIT, RPS) can produce positive results (Paper 2). Often, these instruments are more effective than fiscal/financial, regulatory, or market-based instruments—like carbon prices—but can be costlier to maintain. Thus, rather than on the type, the effectiveness of the instrument depends on its design. Designs that reduce investment risk are typically more effective than designs that increase investment return. Overall, credibility, constant monitoring and evaluation, standardised procedures, and common design elements across policies are key ingredients for effective RE investment policies. In the design, policymakers face a trade-off between technology specificity and technology neutrality. While the former increases technology diversity, it also increases the policy cost. However, from an adaptive market perspective, technology specificity can help the RE financing industry to adopt new technologies and asset classes that would otherwise not be able to attract finance. Therefore, technology specificity can be a valuable tool to enable the transition to low-carbon energy systems.

Finally, policymakers often base their support schemes on techno-economic models. However, if such models do not account for differences in financing conditions between countries and technologies, and ideally the dynamics of financing conditions as well, the resulting policy advice may be biased (Paper 5). Using uniform financing conditions suggests seemingly cost-efficient RE electrification options in developing countries, which may not exist unless policymakers provide guarantees to lower investment risk. Hence, policymakers must ensure that they consult advice which explicitly accounts for financing dynamics.

On policy design

This dissertation has also demonstrated a few general lessons for RE policymakers. First, this dissertation confirms findings from previous studies—that the predictability and stability of policies is essential in providing investment confidence and, hence, improving financing conditions (Papers 2-4). Simultaneously, falling technology costs require flexibility in policy design. In order to avoid a trade-off between predictability and flexibility, policy adjustments must be announced early and must be reasonable (i.e. reflect actual cost reductions). An alternative approach consists of 'adjustment rules' that specify under which (pre-determined) conditions the government is allowed to deviate from existing policies (Jakob and Brunner, 2014). If policies must be changed retroactively (e.g. due to political or budgetary pressure), such changes are costlier in initial technology phases in which the generation costs differ significantly from market prices. Once market prices approach the prices guaranteed by the policy, retroactive changes pose less threat to the RE financing industry. For latecomers, this may that frequent policy changes in the past do not necessarily deter future investment.

Second, committing to a mechanism instead of ad hoc policies can increase policy credibility. For example, policymakers can commit to a rule-based climate finance contribution instead of negotiating the contribution for each round of replenishment in major climate funds (Paper 1). With regard to energy policy, policymakers can commit to thermostatic policies that reflect broader macro-economic situations automatically. For example, RE auctions automatically provide a higher price if financing conditions deteriorate due to macro-economic developments (Schmidt et al., 2019). Above all, standardized procedures and common design elements of policy instruments across sectors and countries enable investors to gain experience more quickly and, consequently, reduce the risk in RE projects (Paper 4). Policymakers must take note of the fact that most large RE projects are financed by international consortia; hence, there are large spillover potentials in the coordination of policies across sectors and countries.

Further thoughts

The literature has shown that socio-economic tipping points are crucial for system transformation, and that such tipping points may be arriving for low-carbon and RE finance (Farmer et al., 2019; Otto et al., 2020). In the current macroeconomic situation, tipping points may coincide with low interest rates, giving RE an edge over FFs, on average. Policymakers could use this window of opportunity and reinforce efforts to deploy RE at scale, potentially in combination with storage. Therefore, large investment programs, such as the European Union's Green Deal or the discussed Green New Deal in the United States, are timely.

Additional efforts must be made to combine policy areas. For example, in carrying out open market operations, central banks could consider favouring green industries (Campiglio et al., 2018) or at least ensuring that their operations are not biased towards FF industries, as they currently are (Matikainen et al., 2017). Further, policymakers could devote more attention to potential synergies between energy policies and financial policies. Ongoing efforts for increasing climate risk transparency (TFCD, 2017) and the design of sustainable financial markets (High-Level Expert Group on Sustainable Finance, 2018) could consider the lessons learned in the development of RE finance markets. For example, it may be important to facilitate learning across the financial industry, share data and ease the entry of new investors in sustainable finance fields, where novel technologies play a role.

Lastly, policymakers must be vigilant not to take the current window of opportunity for granted. Quick and decisive action is required to reach tipping points where RE and low-carbon energy systems will be sustained by the private market (e.g. with the support of a carbon price floor) in the future. As some policymakers consider phasing-out RE support policies (Schmidt et al., 2019), they must refrain from doing so abruptly. Abrupt changes (even temporary), which expose RE to market risk, may threaten RE investment, although RE has reached cost competitiveness with FFs. Further, risk must be phased-in gradually, the success of which depends on the existence of a mature investment ecosystem. It is only in the presence of such an ecosystem that the actors can develop the products and structures required to distribute and manage risk effectively.

5.3 Further research

There is a need for further research to expand on the aspects covered in the papers of this dissertation and solidify a few of the findings. Further research on policy design elements and RE investments would be of interest. Relatedly, scholars could improve the understanding of policy stringency and the relation to design elements. Thus far, measuring the stringency of policy instruments has proven to be a complex endeavour (Carley et al., 2018). Additionally, further research must investigate the dynamics of RE financing conditions and investment risk in markets outside of Western Europe, which are key to the global energy transition. Finally, further research must improve energy system models to include scenario analysis of different financing condition trajectories that could even be matched to existing socio-economic pathways (Bauer et al., 2017). Apart from these direct avenues for further research, there are four areas which are indirectly connected to this dissertation and merit further research.

First, there is a need for conceptual research on RE finance and finance in general. A few empirical observations, such as the importance of experience and network effect in the RE finance ecosystem, suggest that there may be factors at work within the financial industry that efficient market theorems are not able to fully explain. However, a new conceptualisation requires a new theory; thus far there have been only a few attempts at this, and the effects on policymaking remain unclear (Geddes and Schmidt, forthcoming; Mazzucato and MacFarlane, 2019; Naidoo, 2019).

Second, there would be value in a better understanding of the role of finance in historical transitions. Finance plays an important role in any system transformation that requires upfront capital. Conversely, its role becomes more important when the new industry or technology is more capital-intensive compared to the old one. Very large transitions are well documented in energy systems (Fouquet, 2010), and finance booms have occurred in other investment-heavy transitions, such as the British railway extension in the nineteenth century (Campbell and Turner, 2012); however, the role of finance remains poorly understood.

Third, decarbonising other sectors, particularly industry, is a challenging task. The financing involved is very different from RE finance because it involves mainly corporate finance (see section 2.4). However, policy will also likely play a substantial role in the nature and speed of industry decarbonisation, and the conditions on which capital will be made available for such plans are crucial. Future research could investigate the extent to which mechanisms observed in RE finance—such as experience effects, investment ecosystem benefits, or data availability—are crucial for industry decarbonisation as well and could potentially help speeding it up.

Fourth, financing dynamics are influenced by policies, but produce feedback on politics as well (cf. Figure 2). There is evidence of the cost of lobbying and false information of carbon-intensive industries on climate policies (Meng and Rode, 2019; Supran and Oreskes, 2014). If there are certain path-dependent processes within the finance industry, there may be pertinent feedback effects to discover in this industry as well. On a positive note, there may also be large positive feedback from financial players once it is possible to earn money from a new technology; anecdotal evidence from Papers 3 and 4 point in this direction.

Finally, the challenge to keep climate change within safe limits cannot be understated. The required transitions are massive and will touch all economic sectors and the livelihood of people as well. Research and communication, including art, has an important role to play in offering policymakers the options and providing them with the tools to implement these options, thereby creating more positive than negative feedback. The task ahead is to imagine the future after the ‘decisive moment’ depicted in the photo at the beginning of this dissertation. Whether we as a community of scientists, policymakers, and citizens will be able to offer a vision for our lives after this moment will be a crucial factor affecting the chances to transform our societies and to steer into a safe future.

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7 Annex

Annex I: Individual papers (pp. 48)

Paper 1 (p. 48)

Egli, F., & Stünzi, A. (2019). A dynamic climate finance allocation mechanism reflecting the Paris Agreement. *Environmental Research Letters*, *14*(11), 114024. https://doi.org/10.1088/1748-9326/ab443b

Paper 2 (p. 58)

Polzin, F., Egli, F., Steffen, B., & Schmidt, T. S. (2019). How do policies mobilize private finance for renewable energy?—A systematic review with an investor perspective. *Applied Energy*, *236*, 1249–1268. https://doi.org/10.1016/J.APENERGY.2018.11.098

Paper 3 (p. 79)

Egli, F., Steffen, B., & Schmidt, T. S. (2018). A dynamic analysis of financing conditions for renewable energy technologies. *Nature Energy*, *3*(12), 1084–1092. https://doi.org/10.1038/s41560-018-0277-y

Paper 4 (p. 123)

Egli, F. (2020). Renewable energy investment risk : An investigation of changes over time and the underlying drivers. *Energy Policy*, *140*, 111428. https://doi.org/10.1016/j.enpol.2020.111428

Paper 5 (p. 139)

Egli, F., Steffen, B., & Schmidt, T. S. (2019). Bias in energy system models with uniform cost of capital assumption. *Nature Communications*, *10*(1), 4588. https://doi.org/10.1038/s41467-019-12468-z

Annex II: Curriculum vitae (pp. 143)

Paper 1

A dynamic climate finance allocation mechanism reflecting the Paris Agreement

Citation: Egli, F., & Stünzi, A. (2019). A dynamic climate finance allocation mechanism reflecting the Paris Agreement. *Environmental Research Letters*, *14*(11), 114024. https://doi.org/10.1088/1748-9326/ab443b

Contributions: F.E. and A.S. developed the research question, compiled the dataset, developed the burden sharing mechanism and wrote the paper.

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Abstract

Reaching the goal of the Paris Agreement requires substantial investment. The developed country parties have agreed to provide USD$100 billion in climate finance annually from 2020 to 2025. Ongoing negotiations on post-2025 commitments are likely to exceed that sum and include a broader scope of parties. However, there is no guidance regarding the allocation of contributions. Here, we develop a dynamic mechanism based on two conventional pillars of a burden sharing mechanism: emission responsibility (ER) and ability to pay (ATP). The mechanism adds dynamic components that reflect the Paris principle to “ratchet-up” ambition; it rewards countries with ambitious mitigation targets and relieves countries with a high degree of climate vulnerability. Including developed country parties only, we find that ten countries should bear 85% of climate finance contributions (65% if all parties to the Paris Agreement are included). In both scopes, increasing climate ambition is rewarded. If the EU increased its emission reduction target from 40% to 55% by 2030, member states could reduce their climate finance contributions by up to 3.3%. The proposed mechanism allows for an inclusion of sub-, supra- or non-state actors. For example, we find a contribution of USD$3.3 billion annually for conventionally excluded emissions from international aviation and shipping.

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
20 May 2019

REVISED
8 September 2019

ACCEPTED FOR PUBLICATION
13 September 2019

PUBLISHED
6 November 2019

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LETTER

A dynamic climate finance allocation mechanism reflecting the Paris Agreement

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Keywords: climate finance, climate policy, equity principles

Supplementary material for this article is available online

Abstract

Reaching the goal of the Paris Agreement requires substantial investment. The developed country parties have agreed to provide USD$100 billion in climate finance annually from 2020 to 2025. Ongoing negotiations on post-2025 commitments are likely to exceed that sum and include a broader scope of parties. However, there is no guidance regarding the allocation of contributions. Here, we develop a dynamic mechanism based on two conventional pillars of a burden sharing mechanism: emission responsibility and ability to pay. The mechanism adds dynamic components that reflect the Paris principle to 'ratchet-up' ambition; it rewards countries with ambitious mitigation targets and relieves countries with a high degree of climate vulnerability. Including developed country parties only, we find that ten countries should bear 85% of climate finance contributions (65% if all parties to the Paris Agreement are included). In both scopes, increasing climate ambition is rewarded. If the EU increased its emission reduction target from 40% to 55% by 2030, member states could reduce their climate finance contributions by up to 3.3%. The proposed mechanism allows for an inclusion of sub-, supra- or non-state actors. For example, we find a contribution of USD$3.3 billion annually for conventionally excluded emissions from international aviation and shipping.

1. Introduction

In contrast to its predecessor, the Kyoto Protocol, the Paris Agreement requires all parties (i.e. countries) to submit nationally determined contributions (NDCs) outlining what each country considers its fair share of emission reduction and adaptation targets [1]. Achieving the NDCs requires substantial climate finance efforts. The associated problem is threefold: first, the contributing parties have no guidance to determine their fair share; thus the civil society has no tools to evaluate contributions. Moreover, current climate finance pledges may be insufficient to reach the target. Public climate finance is projected to reach USD$67 billion in 2020, with mobilised private climate finance possibly filling the gap [2]. Second, the 2018 United Nations Climate Change Conference (COP24) in Katowice introduced biennial ex-ante communications of climate finance contributions from 2020 onwards [3], reinforcing the need for guidance. Third, the COP24 opened deliberations on a new climate finance target (likely post-2025) [4], reflecting the fact that the USD$100 billion p.a. are most likely insufficient to reach the goal of the Paris Agreement [5] let alone sustainable development goals [6]. Although a higher target seems possible, it may be conditional on a broader scope of contributing parties (see Art. 9, Paris Agreement).

Various researchers have calculated optimal mitigation contributions based on equity principles [7–9] and argue that transparent and equity-based allocation of mitigation responsibilities may increase ambition [10]. However, there is little research offering guidance on how to allocate climate finance responsibility. Current approaches either cover a small set of countries [11] or are based on existing international donor schemes unspecific to climate change, such as the United Nations (UN) [12]. Here, we propose a

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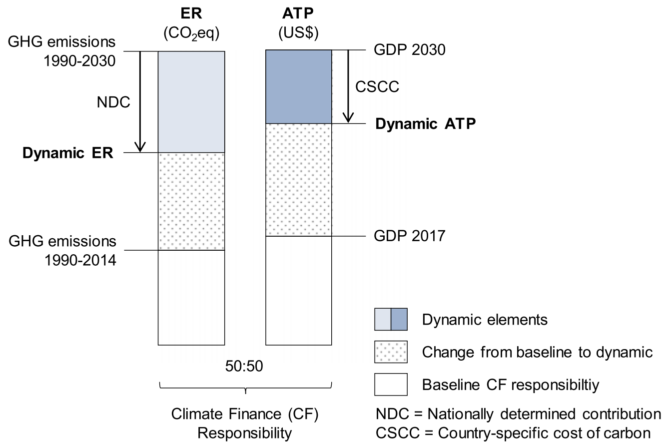

Figure 1. Two pillar climate finance allocation mechanism. ER and ATP are calculated in the baseline specification (white stacks) and the dynamic specification (white plus dotted stacks) separately for each country. Each country's share of the global total is calculated for ER and ATP, and the two shares are weighted equally (50:50) to calculate the share in CF responsibility. For the dynamic ER, we subtract unconditional emission reduction targets from expected total emissions from 1990 to 2030 (change in light blue). For the dynamic ATP, we subtract expected climate damages from expected 2030 GDP (change in dark blue).

novel climate finance allocation mechanism, which provides a benchmarking tool for national deliberations on climate finance contributions. The mechanism embodies the key principles of the Paris Agreement. First, it reflects the principle of common but differentiated responsibilities in providing flexibility regarding the scope of contributors and in accounting for expected future climate damages. Second, it introduces a dynamic forward-looking component that rewards increasing ambition over time (ratcheting-up), similar to policy sequencing to increase stringency over time [13]. Thus, if a country exceeds the average level of ambition, it can thereby reduce its climate finance contribution.

2. Mechanism

We define a baseline specification, which is calculated from historical data on emission responsibility (ER) and ability to pay (ATP) [14]. We use cumulative greenhouse gas (GHG) emissions from 1990 to 2014 to operationalise ER and the gross domestic product (GDP) in 2017 for ATP. We weigh both indicators equally and define a country's share of the total climate finance contribution as the average between the country's share of global cumulative GHG emissions and its share of global GDP (see figure 1 and Methods).

We further define a dynamic specification, where we introduce forward-looking elements for ER and ATP, as illustrated in figure 1. On the left-hand side, ER is extended to cover future emissions up to 2030. Unconditional emission reduction targets submitted in the first NDC of each country are subtracted from ER to calculate the dynamic ER (see Methods). For countries without an unconditional NDC, the dynamic ER is a business as usual (BAU) projection of 2030 emissions. On the right-hand side, we include future climate damages to calculate a climate-adjusted ability to pay in 2030 [15, 16]. We operationalise future climate damages using country-level social costs of carbon (CSCC) and combine these numbers with GDP forecasts to calculate the dynamic ATP (see Methods). The aim of the two dynamic elements is to reward ambitious climate action and to account for future climate change impacts as proposed by De Cian *et al* [17]. Because the total sum of climate finance contributions remains fixed, a more ambitious NDC for one country directly translates into higher climate finance responsibility for the rest (see Methods).

The current climate finance regime (developed countries' pledge to contribute USD$100 billion annually from 2020 onwards) was formalized at the COP16 in Cancun [18]. To reflect this, we define the Cancun scope covering 49 developed countries (see methods and supplementary table 3 is available online at stacks.iop.org/ERL/14/114024/mmedia). To reflect potential future climate finance regimes, we define the Paris scope covering all countries that have signed and/or ratified the Paris Agreement. Finally, we exclude the least-developed countries (LDC) with per capita emissions within a carbon budget consistent with the Paris Agreement (see Methods). The exclusion criteria apply in the Paris scope only and exclude 34 out of 47 LDCs.

3. Methods

This section describes the methodological approach to the mechanism and the data sources. It proceeds in four steps. First, we describe the definition of the scope. Second, we define the baseline mechanism. Third, we describe the dynamic elements. Fourth, we explain the inclusion of bunker fuels.

3.1. Scope

We include all parties that either signed or ratified the Paris Agreement in our analysis ($N = 196$, excluding the European Union). We define two exclusion criteria based on the two pillars described in figure 1. First, we identify countries with 2014 per capita greenhouse gas (GHG) emissions in line with a carbon budget consistent with the Paris Agreement. Specifically, we use the mean of a 2015–2100 carbon budget in line with a >66% chance of limiting global warming to below 2 °C relative to pre-industrial levels [19]. We allocate this budget linearly over 85 years and convert it into per capita budgets using 2014 population data from the World Bank [20]. Second, we identify countries classified as least-developed countries (LDC) by the UN [21]. To classify as a LDC, a country must meet criteria on three dimensions: poverty (Gross National Income (GNI) per capita below USD$1025), weak human resources (e.g. education and health) and high economic vulnerability (e.g. instable agricultural production or export) [22]. Countries fulfilling both exclusion criteria are excluded from the sample. This reduces the sample size from 196 to 164 (see supplementary table 3 for a full list of countries).

Based on the sample of 164 countries, we define two scopes, which we use for all calculations. First, the Cancun scope, reflecting the fact that the pledge to raise USD$100 billion annually from 2020 onwards was formalised at the COP16 in Cancun. The Cancun pledge was made by developed country parties only, which limits the scope to 49 countries. Second, the Paris scope, reflecting the fact that the 2015 Paris Agreement abandoned the bifurcation of the international community in developed and developing countries. Hence, the Paris scope covers all 164 countries. Note, that the scope could also be defined differently and include other actors. For example, emitters of bunker fuels (i.e. the aviation and shipping industry) are currently excluded from emission inventories, but they represented 2.9% of global emissions in 2014 and 3.7% of global GDP in 2017. As an extension we include those two industries as separate actors in the scope and show the distribution of responsibility for all countries and the two industries for the baseline mechanism. Scope adjustments can also be used to include sub-national actors as exemplified in the discussion.

3.2. Baseline calculation

Emission responsibility (ER) is based on the 'polluter pays principle' [23]. Countries that are responsible for large amounts of emissions should also be accountable for the damages they produce and thus contribute more to climate finance. The ability to pay (ATP) or capacity principle reflects a long tradition of tax schemes worldwide based on the notion that actors should pay in proportion to their capacities [14]. We conceptualise ER as total emissions in GHG-equivalent, excluding emissions from land use, land-use change and forestry (LULUCF) from 1990 to 2014 [24]. Several scholars and nongovernmental organisations propose dating emissions further back to 1900 or 1850. We follow the scientific literature in starting to assign responsibility when climate negotiations started, thus 1990 [25]. Where emissions data is unavailable, we search for online sources and complement the data manually for Monaco [26] and San Marino [27].

To represent ATP, we use GDP data for 2017 in constant 2010 USD from the World Bank [28]. Where World Bank data is unavailable (Cook Islands, Cuba, Djibouti, Eritrea, Liechtenstein, Monaco, Democratic People's Republic of Korea, Somalia, South Sudan, Syrian Arab Republic, Venezuela and Yemen), we use UN data from 2016 [29]. The resulting dataset contains 159 countries and excludes Andorra, Niue, South Sudan, Timor-Leste and West Bank Gaza due to a lack of data.

We calculate the share of climate finance responsibility F for each country i according to equation (1) and impose equal weights for the two pillars.

$$F_i = \left(\frac{\mathrm{ER}_i}{\sum_{n=1}^{N} \mathrm{ER}} + \frac{\mathrm{ATP}_i}{\sum_{n=1}^{N} \mathrm{ATP}} \right) \Big/ 2. \tag{1}$$

For the purpose of this paper, F is multiplied with the annual climate finance commitment from 2020 to 2025, hence USD$100 billion.

3.3. Dynamic elements

The dynamic elements add a forward-looking component to both pillars. Namely, we add emission commitments for 2030 to the ER pillar and expected climate damages in 2030 to the ATP pillar. For ER, the first pillar, we search for publicly available *unconditional* NDCs—hence, emission reduction commitments for 2030. In the first step, if a country has submitted an NDC, we calculate the total emissions from 2015 to 2030, assuming a linear annual decrease/increase from the 2014 level of emissions (67 countries submitted either an absolute emission target for 2030 or a target relative to historic emissions, and 25 countries submitted an emission target relative to the BAU). If a country has not submitted an NDC, we use a BAU scenario instead ($N = 68$) and follow the same procedure. By considering unconditional emission reduction targets only, we avoid conflicting targets that could arise from using targets conditional on climate finance. Projected emissions by 2030 were directly read from the NDC targets [26] and, if necessary, calculated as shares from BAU scenarios. BAU scenarios were taken from the NDCs if available; otherwise they were taken from estimations by the Climate Equity Reference Project (CERP) [27]. National targets expressed as emission intensities were translated to total emissions based on GDP projections from the ETH Climate Calculator [30].

In the second step, we add future emissions to historic emissions to calculate the new ER from 1990 to 2030 for each country. To do so, we calculate the average emissions over 16 years (2014–2030) that map the emission path until 2030 as submitted in the country's NDC. Equation (2) describes the new ER for each country *i*, where *NDC* is replaced by *BAU* in case a country has not submitted an unconditional NDC.

$$\mathrm{ER}_{new,i} = \mathrm{ER}_{old,i} + \left[\mathrm{GHG}_{2014,i} + \frac{\mathrm{NDC}_{2030,i} - \mathrm{GHG}_{2014,i}}{2}\right] \times 16. \tag{2}$$

For ATP, the second pillar, we use GDP forecasts for 2030 [30], country-specific costs of carbon [16] and 2030 emission forecasts using the above result according to equation (3), where again *NDC* is replaced by *BAU* if no NDC exists.

$$\mathrm{GHG}_{2030,world} = \sum_{n=1}^{N} \mathrm{NDC}_{2030,i}. \tag{3}$$

We calculate the new ATP for each country *i* according to equation (4) by allocating the marginal costs of each ton of GHG emissions to countries via the country-specific social cost of carbon (SCC) from Ricke *et al* [16] and subtracting expected climate damages from expected GDP in 2030. Note that this is an economic conceptualisation of vulnerability.

$$\mathrm{ATP}_{new,i} = \mathrm{GDP}_{2030,i} - \mathrm{GHG}_{2030,world} \times \mathrm{SCC}_{2020,i}. \tag{4}$$

Note that due to data availability, the SCC estimates are for 2020 instead of 2030. Assuming increasing economic damages with increasing global temperatures, this yields a conservative estimate of climate damages in 2030. We use a median SCC estimate of an average scenario assuming a middle of the road socioeconomic pathway (Shared Socio-economic Pathway scenario 2, SSP2) and the closest corresponding climate scenario (Representative Concentration Pathway 6.0, RCP6.0), a pure time preference of 2% and an elasticity of marginal utility of 1.5 [16]. Where Ricke *et al* [16] does not provide a country-specific SCC, we use the median value (28 countries). Because this implies using median values for 19 of the 39 Small Island and Developing States (SIDS), we verify whether the SCC for SIDS differs from the median. The SCC for SIDS is slightly below the median, we hence do not penalise SIDS.

The two forward-looking elements can introduce a trade-off: a more ambitious NDC, reducing future global emissions, reduces future damages and hence increases future ATP. However, applying equations (2) and (4) to the data, it can be shown that the effect of reduced domestic emissions through the ER is stronger than its effect on ATP via reduced global emission, ensuring the dynamic efficiency of the mechanism.

3.4. Bunker fuels

To include bunker fuels, we draw on emissions data for the international aviation and shipping industries. Due to a lack of forward-looking data, we compute only the baseline allocation. For aviation, we estimate the cumulative emissions in 2014 from the IPCC 2014 report [31], assuming linear growth similar to the growth rates from 1990 to 2012. We do not include a radiation factor and hence provide a conservative estimate. For shipping, we estimate cumulative emissions based on the data from the International Maritime Organization [32], with an emission growth rate of 2.4% between 2013 and 2015 [33]. To approximate the ATP, we estimate the aviation share at 3.5% of global GDP 2017 [34]. For shipping, we estimate the share of global GDP 2017 at 0.3% [35]. Although this approach ensures a more complete accounting of global emissions, it comes with the caveat of a small double counting on the ATP, primarily affecting large economies. There is currently no data available to allocate international aviation and shipping industries to domestic GDP in a consistent manner to alleviate this concern.

4. Results

Figures 2(a) and (b) show the top ten contributors in the Cancun and Paris scope, respectively (see supplementary tables 1 and 2 for the contributions of each country in both scopes). In the Cancun scope, ten countries are responsible for 84% of total climate finance and 21 for 95%. The US covers 39%, followed by Japan (9%) and Russia (8.5%), Germany (6.5%), the UK (4.5%) and France (4%). The EU as one entity would be responsible for 32%. In the Paris scope, 10 countries together contribute 65% of the climate finance contributions and 60 countries contribute 95%, with the US and China accounting for 38%. All G20 countries together represent 77% of the contributions, whereas African countries contribute 4.5%. The EU as one entity would be responsible for 15%.

Figures 2(b) and (d) show the change in climate finance contributions when including the dynamic elements for both scopes. Countries coloured in blue benefit from including the dynamic elements, countries in red suffer. In the Cancun scope, 28 countries benefit and 21 suffer from the inclusion of dynamic elements (83 and 76 in the Paris scope, respectively). To analyse the effects more systematically, figure 3 shows the ten most affected countries for both scopes and reveals that the choice of scope is crucial. For Russia and the US, the effect of including dynamic elements reverses depending on the scope. In the Cancun scope, these countries would face a higher contribution in a dynamic setting; in the Paris scope, the opposite is true. There are two reasons for this. First, compared to the average developed country, these countries have unambitious emission reduction

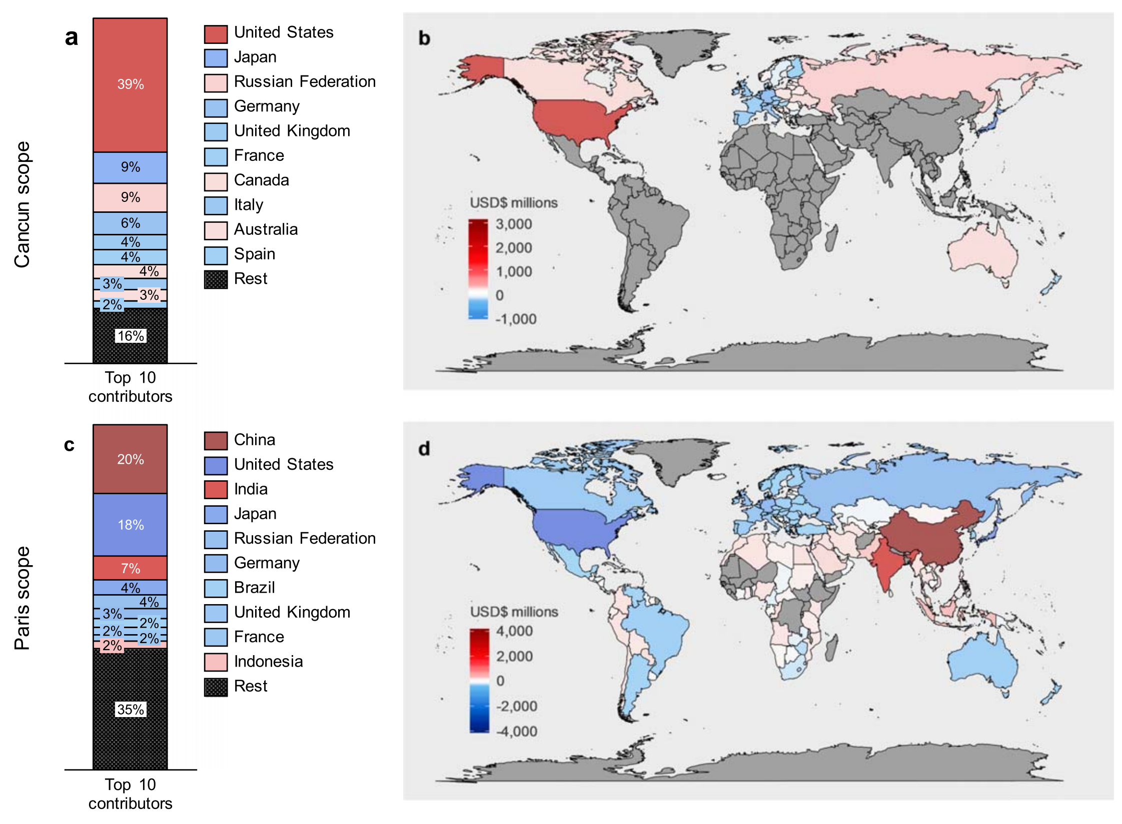

Figure 2. Climate finance responsibility for Cancun and Paris scope. (a) Shares in climate finance responsibility for the top ten contributors and the rest in the Cancun scope. (b) Change of responsibility in millions of USD$ (constant 2010) from baseline to dynamic mechanism in the Cancun scope. (c) Shares in climate finance responsibility for the top ten contributors and the rest in the Paris scope. (d) Change of responsibility in millions of USD$ (constant 2010) from baseline to dynamic mechanism in the Paris scope.

targets. However, when compared to emission-intensive economies on a growth path, such as India for example, their expected emissions are lower. Second, the Paris scope contains emerging economies that typically grow faster than developed economies. Hence, the developed countries' share of world GDP decreases over time in the Paris scope, reducing their future ATP (in relative terms). In addition, some countries, such as Russia, benefit from climate change, which increases their future ATP.

For other countries, such as the EU and Japan, the direction of the effect does not change depending on the scope. For the EU, the responsibility decreases by 5% and 18% for the Cancun and Paris scopes, respectively. For Japan, the decrease amounts to 10% and 23% for the Cancun and Paris scopes, respectively. In the case of the EU, this is the result of ambitious emission reduction targets and high climate vulnerability; in the case of Japan, it is mainly due to its coastal exposure and the high climate vulnerability. On the other hand, China increases its contribution by 24% due to its relatively lower emission reduction ambition, higher economic growth and lower vulnerability.

The substantial changes due to dynamic ER illustrate the rewards for ambitious NDCs. For example, Moldova's contribution is reduced by 17% due to its high-ambition NDC. On the other hand, Paraguay contributes almost 2.5 times as much (USD$140 million) compared to the baseline (USD$59 million) due to the relatively high projected 2030 emissions under a BAU scenario in their NDC. As such, one can calculate the potential for future action: Paraguay could reduce its climate finance contribution by 15% (USD$20 million) by increasing its emission reduction target from 10% to 30%. More generally, 21 countries in the Paris scope *only* have an NDC *conditional* on international support (e.g. climate finance). If all of them implemented an unconditional NDC of 15% compared to BAU 2030 (average of the rest) instead, they could reduce their climate finance responsibility up to 7% (e.g. Pakistan: 7%, Kenya: 4%). Similarly, if the EU increased its emission reduction target from 40% to 55%, some of the member states' finance responsibilities would decrease by up to 3.3% (e.g. Estonia and Bulgaria).

Finally, the proposed mechanism can be extended to include the international aviation and shipping industries (see Methods). We find that the climate finance responsibilities of international aviation and international shipping amounts to USD$2.2 billion and USD$1.1 billion, respectively, placing both among the top 20 contributors (Paris scope, baseline calculations).

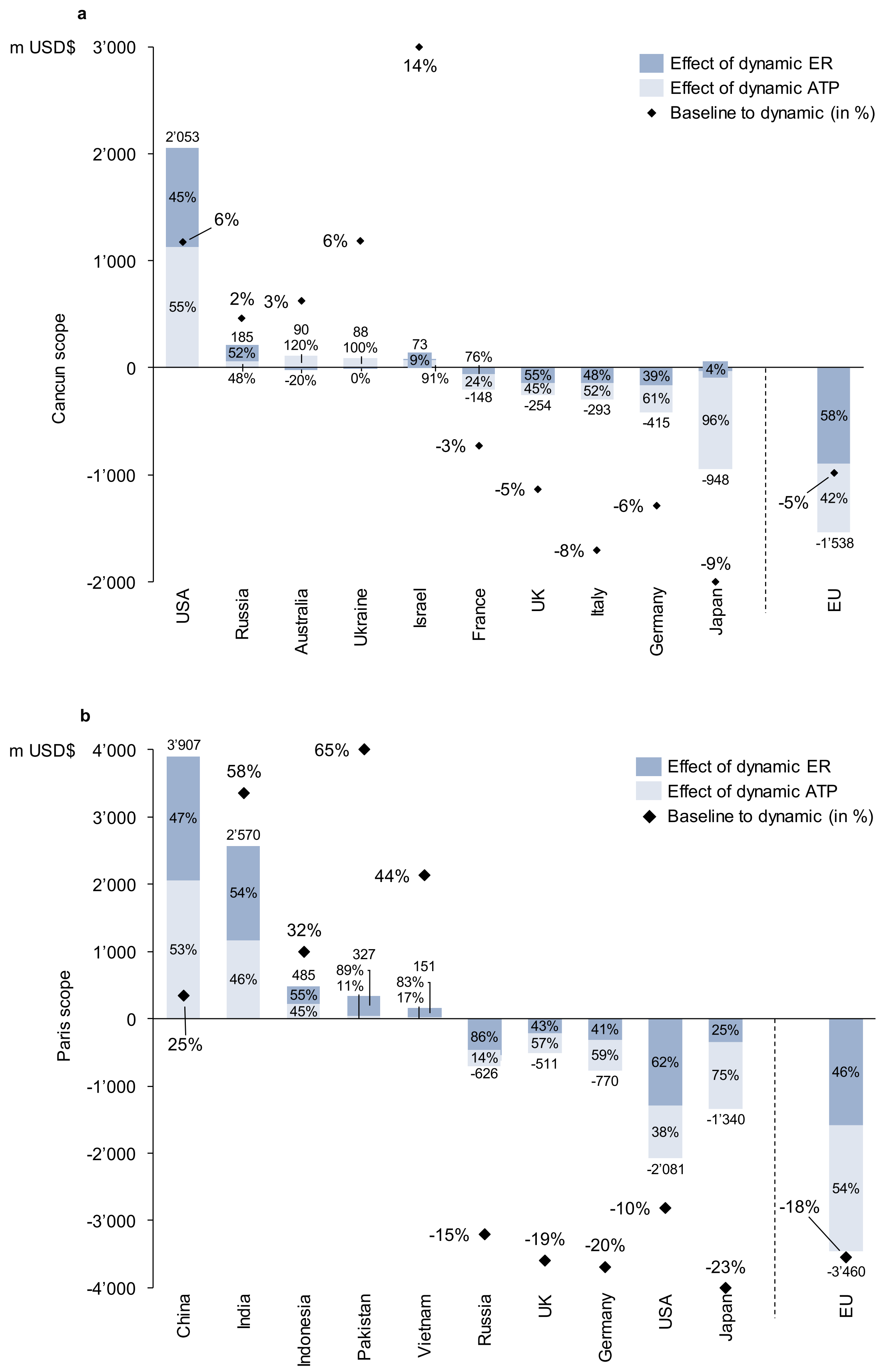

Figure 3. Changes in climate responsibility from baseline to dynamic mechanism. (a) Changes (absolute and in percent relative to baseline) for the ten most affected countries and the EU in the Cancun scope. (b) Changes (absolute and in percent relative to baseline) for the ten most affected countries and the EU in the Paris scope. The total change is given in millions of USD$ (constant 2010); diamonds denote the corresponding percent change. Stacked bars indicate the relative contributions to the total change of ER and ATP.

5. Discussion

Our findings reveal four insights: First, several European countries have pledged more than the amounts calculated in the Cancun scope (e.g. Germany pledged USD$10 billion instead of USD$6.4 billion, France pledged USD$5 billion instead of USD$4.2 billion) [36, 37]. However, for other European countries, the pledges are insufficient in the current contribution scheme. Namely, Switzerland would need to increase its contribution by USD$339 million to reach USD $789 million (+75%) [38]. Moreover, the US plans to spend about USD$2 billion in 2019 [39], one ninth of what is required in the Paris scope and one eighteenth of what is required in the Cancun scope. To lay the foundation for a post-2025 framework with a broader scope, developed country parties may need to legitimate this discussion by stepping up current contributions to their fair share for the 2020–2025 period.

Second, our results for the Paris scope show that some countries currently claiming financial support may have to acknowledge that they will need to contribute instead in a post-2025 framework due to their ER and ATP. Pakistan, for example, claims that it would need about USD$40 billion in assistance to reach its conditional emission reduction target of 20% compared to BAU 2030. However, according to our results, Pakistan would have a climate finance responsibility of around USD$830 million per year in the Paris scope.

Third, two thirds of all countries use vulnerability to explain their (small) mitigation and adaptation efforts [1]. Accounting for future vulnerability may therefore alleviate some of these concerns and make political consensus easier. However, fewer countries benefit from including vulnerability in the mechanism ($N = 64$) compared to including NDCs ($N = 96$). Hence, according to the proposed mechanism, ambitious NDCs help more countries lower their climate finance responsibility than vulnerability does.

Fourth, the mechanism provides an incentive to peer-review the implementation of NDCs, in line with insights regarding policy surveillance [40]. Countries that implement their NDCs and incur related costs will want to ensure that other countries follow up on their commitments so that they avoid overpaying within the climate finance mechanism. In the absence of an international body with oversight and sanctioning capacity, increasing incentives for peer-reviewing NDCs will be crucial to achieve substantial emission mitigation.

These four insights relate to a broader political science literature. Three refer to the question of fair burden sharing, while one links to effective international governance. Mitigating climate change depicts a public good provision dilemma. Despite altruistic motivation to contribute to the public good [41], there is an incentive to free-ride on other countries' efforts and procrastinate climate action to future governments [42]. Scholars assign the success of an agreement to strong leadership [43] and intentionally sticky policy design [44]. A commitment to a mechanism instead of an ad hoc climate finance contribution may be more successful in 'tying successors' hands' and therefore lock-in the policy regime [42]. Moreover, a public commitment to the mechanism could create leadership on the issue that may lead to other countries learning from the experience, imitating the leaders or even responding to coercion from leaders; patterns that have been observed in policy adoption among cities [45]. Lastly, the mechanism provides the civil society and countries with a tool to check the adequacy of a governments' climate finance contribution. Such reviewing and subsequent naming and shaming can also be important to ensure more effective international collaboration [46].

The allocation mechanism builds on the most common equity principles, namely the ability to pay (or capacity) principle and the polluter pays principle (including historic responsibility). These two principles are also among the most frequently used when countries explain the fairness of the contribution in their NDC [1]. Moreover, the mechanism relates to other principles, which are debated in the literature, too [14]. For example, the egalitarian principle is applied to define one exclusion criterion (per capita emissions in line with a 2°C carbon budget). The merit principle is reflected in the forward-looking element, rewarding countries that have ambitious emission reduction paths. The right to development principle is also partly reflected. On the on hand, by excluding LDCs with emissions in line with a 2°C carbon budget from the pool of contributors and on the other hand, by accounting for future climate vulnerability. Lastly, the cost sharing principle demands that emissions are reduced where abatement costs are lowest. This principle is not reflected in the mechanism, because the mechanism abstracts from the debate on where to allocate the funds geographically and whether to allocate them to mitigation or adaptation efforts. The proposed mechanism also does not make a claim on the type of finance that should be used [47]. Overall, the mechanism focuses on the allocation of climate finance responsibility based on the two most common equity principles.

Future research could propose additional criteria—such as green finance or green research and development—to be included as dynamic elements and analyse conditions for political feasibility. Additionally, future research could address the issue that some national governments have threatened or decided to withdraw from the Paris Agreement, but several subnational actors have committed to remaining in the Agreement. For example, the United States have submitted their withdrawal to the Paris Agreement, which will take effect in late 2020. In response, a coalition of US States has formed the US Climate Alliance to maintain their commitment irrespective of the federal decision. Conditional on data availability, our mechanism would be flexible to including sub-national actors, which play an increasingly important role in pursuing ambitious climate policies [48, 49]. Moreover, future research could investigate how to deal with domestic emission reduction targets versus international compensation schemes, how to account for differences in consumption-based GHG accounting compared to the commonly used production-based approach [50] or how to better reflect the need for short-term mitigation targets by accounting for differences in warming potentials [51].

6. Conclusion

A common understanding of climate finance responsibility will be vital to the successful mitigation of and adaptation to climate change. In this paper, we propose a mechanism for evaluating the adequacy of current climate finance pledges. Furthermore, the mechanism creates co-benefits beyond secured and stable finance, particularly in the form of incentives for ambitious emission reduction targets and peer-reviewing their implementation. The mechanism is designed to fit the Paris architecture. First, the mechanism is based on established principles to allocate responsibility, increasing the likelihood of acceptance. Second, its design is Paris-compatible in that it uses forward-looking elements to reflect the 'ratcheting-up' of ambition over time. Third, it offers a transparent and tractable method to calculate climate finance contributions. Fourth, these contributions can be calculated in regular time intervals, reflecting the five-year stocktake envisaged in the Paris Agreement or the planned biennial climate finance communication. Fifth, the mechanism is open to extensions in scope, such as bunker fuels or other sub-, supra- or non-state actors.

To policymakers, this paper provides a tool to commit to a rules-based climate finance contribution, making the commitment more robust and potentially more sustainable. In committing to the mechanism, policymakers should be aware of the importance of accurate and timely data. For example, emissions data should be readily available (incl. LULUCF) and targets (e.g. NDCs) should be comparable. More work is needed on the international level to attain these goals. Most importantly, a consensus on the definition and the accounting of climate finance will be required in order to have a meaningful comparison of climate finance contributions across countries. Lastly, this paper stresses the importance of conventionally excluded sectors, such as international aviation and shipping, which are responsible for large shares of global emissions. It is questionable whether the current separate negotiation track through the ICAO and the IMO will deliver commitments that honour adequate climate finance contributions of these sectors.

Acknowledgments

The authors thank seminar participants at the University of Graz, participants of the envecon 2019 in London, two anonymous reviewers in the Swiss Federal Office for the Environment and the State Secretariat for Economic Affairs, members of the Chair of Economics and Resource Economics and members of the Energy Politics Group at ETH Zurich for helpful comments on earlier drafts of the paper.

Author contributions

Both authors contributed equally.

Data availability

The data used in this paper are available from the authors upon reasonable request.

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Paper 2

How do policies mobilize private finance for renewable energy? – A systematic review taking an investor perspective

Citation: Polzin, F., Egli, F., Steffen, B., & Schmidt, T. S. (2019). How do policies mobilize private finance for renewable energy?—A systematic review with an investor perspective. *Applied Energy*, *236*, 1249–1268. https://doi.org/10.1016/J.APENERGY.2018.11.098

Contributions: All authors developed the research idea. F.E., together with the other authors, conceptualized the research design. F.E. surveyed the qualitative evidence; F.P. surveyed the quantitative evidence. F.P. and F.E. took the lead in writing.

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Abstract

With the urgency of climate change, and billions spent globally on renewable energy (RE) support policies, it is crucial to understand which policies are effective. Substantial research on RE deployment policies has been carried out over the last two decades, resulting in inconclusive findings regarding the effectiveness in mobilizing private finance. Here, we take a novel perspective and review 96 empirical studies concerning the impact of policies on two key investor decision metrics: investment risk and investment return. Only if both metrics correspond to the investors' expectations are they willing to engage in RE projects. First, our rigorous literature review shows that effective policies address risk and return simultaneously. Second, we find that generic instrument design features, such as credibility and predictability (continuous evaluation and monitoring), considerably impact investment risk. A more focused analysis of the specific design elements of feed-in tariffs, auctions and renewable portfolio standards reveals that these instruments are most effective if designed in a way in which they reduce RE project risk while increasing return. We distil important implications for policymakers who aim at fostering renewable energy and clean technologies more broadly.

Applied Energy 236 (2019) 1249–1268

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

How do policies mobilize private finance for renewable energy?—A systematic review with an investor perspective

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HIGHLIGHTS

- This study reviews the effectiveness of policies for renewable energy investments.
- We analyse the impact of policies on investment risk and investment return.
- We separate the effect of policy design elements on investment risk and return.
- The study has important policy implications for a privately financed energy transition.

ARTICLE INFO

Keywords:
Renewable energy
Investment
Policy design
Risk-return
Feed-in tariff
Renewable portfolio standards
Auctions

ABSTRACT

With the urgency of climate change, and billions spent globally on renewable energy (RE) support policies, it is crucial to understand which policies are effective. Substantial scholarly research on RE deployment policies has been carried out over the last two decades, resulting in inconclusive findings regarding the effectiveness of mobilizing private finance. Here, we take a novel perspective and review 96 empirical studies concerning the impact of policies on two key investor decision metrics: investment risk and investment return. Only if both metrics correspond to the investors' expectations are they willing to engage in RE projects. First, our rigorous literature review shows that effective policies address risk and return simultaneously. Second, we find that generic instrument design features, such as credibility and predictability (continuous evaluation and monitoring), considerably impact investment risk. A more focused analysis of the specific design elements of feed-in tariffs, auctions and renewable portfolio standards reveals that these instruments are most effective when they are designed in such a way that they reduce RE project risk while increasing return. We distil important implications for policymakers who aim to foster renewable energy and clean technologies more broadly.

1. Introduction

Most policymakers and scholars agree that keeping global warming 'well below' two degrees Celsius as specified by the Paris Agreement and the corresponding transition of the global economy will require large-scale private investment in renewable energy (RE) from a broad range of investors [1–3]. While private investment is critical for deployment [4], the academic debate over the last 20 years has mainly analysed RE deployment policies without explicitly considering investment decision metrics. Broadly speaking, empirical studies assessed policies regarding their effectiveness, efficiency and other socio-economic goals [5–8]. Within this scope, the question of whether quantity or price-based instruments are more effective or efficient has been at the centre [9–11]. From there, scholars embarked on a trajectory comparing effectiveness of individual instruments in different contexts [e.g. 12,13], as well as in large-scale country-level analyses [e.g. 14–16]. These studies reveal inconclusive results regarding which instruments to use. At the same time, we witnessed a surge in the implementation of policy instruments around the globe with around 80% of high- and upper-middle-income countries adopting RE support policies [17,18].

A separate stream of literature has discussed the relationship between risk and return of a project and its link to investor engagement in renewable energy projects [19–22]. Financial economists generally agree that risk and return are the fundamental determinants for private investors [23–25]. Policy instruments can therefore affect investors'

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https://doi.org/10.1016/j.apenergy.2018.11.098
Received 30 May 2018; Received in revised form 30 September 2018; Accepted 27 November 2018
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behaviour by either reducing the risk of a RE project, increasing the return or both [26–28]. While the decision metrics of investors are well-known, systemic knowledge about the dedicated effect of RE policy on investors remains scarce [29–32]. To address this gap, we focus on the following research question, analysing existing empirical evidence: *How do RE support policies influence RE project investment risk and investment return?*

In a first step, we perform a review of the qualitative and quantitative empirical RE policy literature, focusing on the effect of 18 different instrument types on risk and return. This paper is the first review to systematically analyse RE policy support, such as fiscal and financial instruments, market-based instruments and regulations regarding their risk and return implications. One important finding that emerges from this literature review is that very effective instruments reduce the risk while increasing the return. We also find that beyond policy instrument types, the specific policy designs [see 33–35] have major implications on the investment decision metrics. In a second step, we therefore carry out an in-depth analysis of the design elements of the three most important instrument types previously identified: feed-in tariffs (FITs), auctions for power purchase agreements (PPAs) and renewable portfolio standards (RPSs). We find that—independent of instrument type—policy designs that reduce risks have a strong impact on investments. The empirical evidence gained through our review allows us to derive recommendations for policymakers.

The remainder of this paper is structured as follows: Section 2 introduces our analytical framework, which forms the basis for our methodology to assemble the literature base (Section 3). Section 4 describes the sample of empirical studies. While Section 5 reports the results of the review of policy instrument types, Section 6 reports the results on RE policy design options. Conclusions and policy implications are drawn in Section 7.

2. Investment decisions and the effects of policy instruments and designs

2.1. Altering the risk-return profile to catalyse RE investments

In professional investment decisions, expected return and the associated risk are the most important metrics when describing the attractiveness of investment opportunities such as RE projects [22]. Thereby, 'risk' is (implicitly) conceptualized as the effect of an unpredictable event on the project value, considering both the probability of possible events and their financial impact in the case that they materialise [36]. The finance literature has long established a positive relationship between investment risk and return in theory [37] and, more recently, empirically [23,24]. Especially in project-finance setups, which are particularly important for RE investments, higher project risks translate directly into higher required returns [38,39], because the only collateral available to financiers is the RE asset and its expected future cash flows [40]. In line with previous literature on renewable energy investment [19,20,22], we focus in this review on idiosyncratic risk (and not portfolio risk). Generally, infrastructure assets such as RE projects tend to exhibit lower market risk but higher idiosyncratic risk than other asset classes [41]. This detachment from market risks implies a portfolio diversification benefit from infrastructure investments per se. If an investor thus decides to invest in infrastructure, each project is evaluated based on its risk-return characteristics in order to make the investment decision. Therefore, the relevant unit of analysis remains the project, even though an investor may hold a portfolio. Fig. 1 shows a conceptual framework regarding the relationship of risk (x-axis) and expected return (y-axis), including a market line describing investment alternatives (blue line). With higher risks, an increasing risk premium is expected on top of the risk-free rate, often calculated as the yields of United States treasury bonds with a 30-day maturity [42]. When presented with an investment opportunity, a professional investor would go ahead and invest if a project reaches the market line but refrain if it is below the line (red area). The exact threshold would depend on individual investors' preferences (e.g. risk aversion).

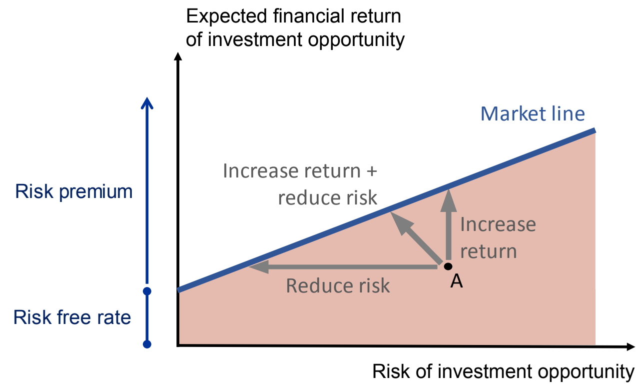

Fig. 1. A risk-return framework and policy options to attract investments.

In order to make unattractive projects (e.g. A in Fig. 1) viable for investment, policy instruments can act in three ways: (i) increase the return (upward arrow), (ii) reduce the risk (leftward arrow) or (iii) a combination of the former and the latter (cf. [43,27]). Reducing risks, and thereby lowering the investment hurdle rate, is particularly important for RE investments due to their high upfront capital and resulting high financing requirements [26,27,44]. This review therefore uses the risk-return framework to classify empirical results. It does so by focusing on professional investors, because they account for 53% of global non-hydro renewable energy investments [45].

2.2. Policy instrument design

While the role of different instruments for inducing RE investment is discussed widely in the literature (see Section 5), design elements are poorly covered, with a few exceptions [46]. Innovation scholars have long been arguing that the effects of a policy do not only depend on the instrument type but also on its design [33,47–50]. For instance, a FIT for solar photovoltaic (PV) which exceeds the generation cost of that technology is more likely to result in a larger investment than one that is too low to compensate for all costs. More generally, public policy literature describes how any policy instrument can be understood as a composition of design elements [51]. While this literature analyses design features on three levels of abstraction [52], here we focus on the level of 'on-the-ground-measures,' which describe 'settings' (e.g. height of specific targets and target groups) and 'calibrations' (e.g. levels of subsidies). Although only a few papers exist which systematically analyse the role of policy design features on investment decisions, many empirical studies implicitly cover the role of design features.

Prior studies have focused on the distinction between policy effectiveness and economic efficiency [53,54]. The former generally refers to a substantial increase in deployment and investment. The latter emphasizes the fact that capacity should be generated at decreasing competitive cost due to learning but should also be considered from a societal point of view [55]. This includes a range of market failures and externalities as secondary policy goals, such as achieving technological improvements over time [56], generating employment [57], increasing actor diversity [58] or improving energy access [59,60]. In this paper, we focus on policy effectiveness, as existing evidence from empirical studies mainly refers to the question of whether policies lead to investment. Empirically establishing policy efficiency (i.e. also including societal policy cost and comparing it with alternatives) is beyond the scope of most empirical evidence so far. Based on the considerations in this section, we developed a methodology to assemble the literature base, which is discussed below.

3. Methodology

We conduct a systematic review of existing evidence to analyse how policy interventions mobilise private RE investors and specifically add the novel perspective on risk/return mechanisms for policy effectiveness. This article applies a semi-structured method, commonly used in the social sciences, to assemble the literature base [61–63]. It provides a more transparent, reliable and replicable way of selecting literature than the classical narrative review [64], while being less structured and more flexible than a meta-analysis [65]. It follows a sequence of steps searching for literature and applying inclusion and exclusion criteria guided by our analytical framework [cf. 61,66] (see Section 2.1).

Our semi-structured literature search is based on a 'Scopus' search using broad terms [67][1], existing reviews, empirical papers and a follow-up snow-balling of cited literature therein [68]. We screened abstracts of the resulting literature according to the scope of the literature review and included only those published peer-reviewed articles that were available (at least online-first) by August 2018. According to Hunter and Schmidt [65], this does not lead to an 'availability bias' for empirical studies if a sufficiently large article base is considered. In this case, the direction of the published and unpublished results tends to be similar.

We exclusively focus on empirical papers with primary (new) quantitative or qualitative data and/or analysis. Whereas quantitative studies provide a clear picture on effectiveness (size of effect), qualitative evidence is needed to understand the impact of policy instruments on RE investments via the risk and return factors. Geographically, only investment grade countries and the four BASIC emerging economies of Brazil, South Africa, India and China are considered in our analysis. Investment decisions in more risky (non-investment grade) countries are driven by very different factors (e.g. the involvement of development banks) [69,70]. This procedure, based on our inclusion criteria, resulted in a longlist of 135 articles.

Articles were then systematically analysed and the meta-data extracted [61,66]. A team of three independent researchers coded the literature and developed a comprehensive database containing information about findings (research question, key results, limitations/validity), method and scope (quantitative/qualitative/mixed, unit of analysis, data source, dependent variable, period under study and regional scope), technologies (e.g. wind onshore/offshore, solar PV, concentrated solar power [CSP]), instruments (e.g. FIT, investment credit, green certificates) and their impact on investment decision metrics (effects on investment, risk mitigation and return component). To ensure consistency of the coding and analysis process, the three coders frequently met and discussed potential ambiguities [cf. 61]. In case of disagreement between two coders, additional members of the research team were consulted.

From the longlist, we excluded papers that looked at drivers and barriers of RE in a general manner only, along with articles that did not implicitly or explicitly evaluate policy instruments. Lastly, we also excluded papers with an innovation (and not deployment/investment) focus to arrive at the final set of 96 articles. These articles are described in further detail in the next section.

4. Overview of the identified literature

Two decades of research have produced a large and heterogeneous body of literature amounting to 35 qualitative, 57 quantitative and 4 mixed-methods papers (see Table 2 for a detailed overview of the instruments and their effects on risk and return). We differentiate these papers according to the paper's country scope and the empirical method applied. Two main types of analyses emerge: large-n comparisons, using regression techniques or other quantitative methods, and small-n comparisons or single-country studies using document-based or interview-based methods (see Fig. 2).

Concerning regional scope, the identified literature covers the European Union (EU) (44 articles), the United States (US) (19), the entire Organisation for Economic Co-operation and Development (OECD) (8), emerging economies (11) and global sets of countries (13). Studies of EU/US/OECD, as well as global studies using more aggregated policy measures, appear frequently amongst the large-n studies, most likely driven by data availability. Consistent with the expansion of RE capacity [17], most of the empirical articles subjected to this review were published between 2010 and 2018 (see Fig. 3).

Fig. 4 reveals that, in the empirical literature, most research articles cover onshore wind, followed by studies focusing on RE in general. Solar PV is analysed by significantly fewer articles, which might be due to the fact that solar PV technologies have only been deployed on a utility-scale since 2008–2010. Biomass and waste-to-energy (W2E) (23) and geothermal (14) have been analysed by over 10 studies and thus have been subject to substantial academic analysis. Other technologies, such as small hydro, have been covered only by a few studies. This corresponds to actual deployment and investment over the period from 2013 to 2016. Significant investment has also gone into offshore wind and concentrated solar power (CSP) projects (see right chart in Fig. 4). Thus far, the drivers of these investments have been analysed by very few academic papers.

Policy instruments that support RE can be categorized by several dimensions [29,71,72]. Here, we use a simplified version of the International Energy Agency (IEA) and International Renewable Energy Agency's (IRENA) Policies and Measures classification [73]. Compared to other classifications which consider the underlying economic logic of instruments [e.g. 74], the practice-oriented typology of IEA/IRENA seems more appropriate for our review from an investor's standpoint. Table 1 provides an overview of the classification and provides a definition for each instrument. While many instrument types directly support RE (e.g. direct investment or FITs), others increase the attractiveness of RE vis-à-vis fossil fuel-based power generation technologies by decreasing the revenues and/or increasing the risks of the latter (e.g. carbon tax or greenhouse gas [GHG] certificates).

FITs, tax credit/relief and auctions represent the most widely analysed economic policy measures, while scholars pay particular attention to quotas and RPSs. Other instruments, such as market-based instruments (carbon and green certificates) and direct public investment and support (information, long-term planning, RD&D), have played a subordinate role in empirical studies to date (see Fig. 5 for an overview).

[1] Scopus search 1: 'renewable energy deployment,' policy; Scopus search 2: 'renewable energy investment,' policy.

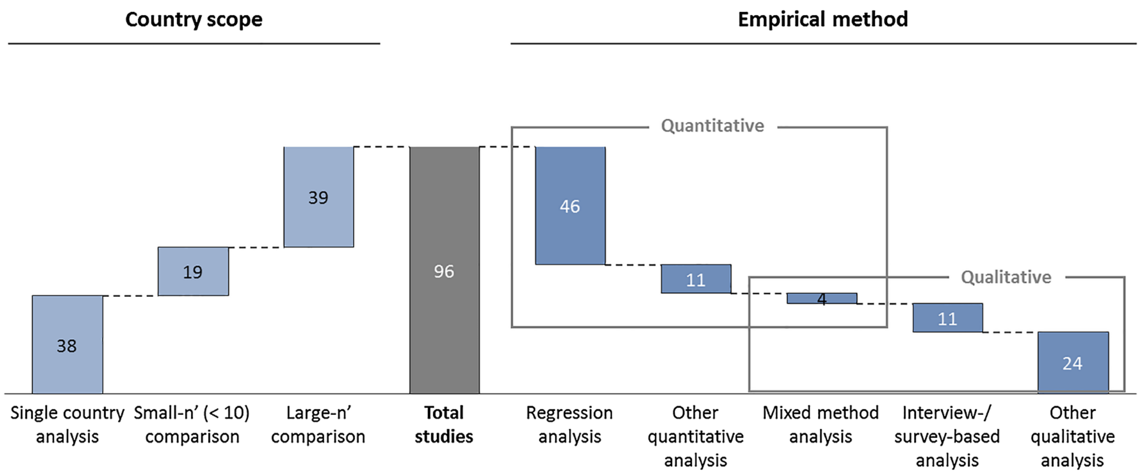

Fig. 2. Overview of research approaches.

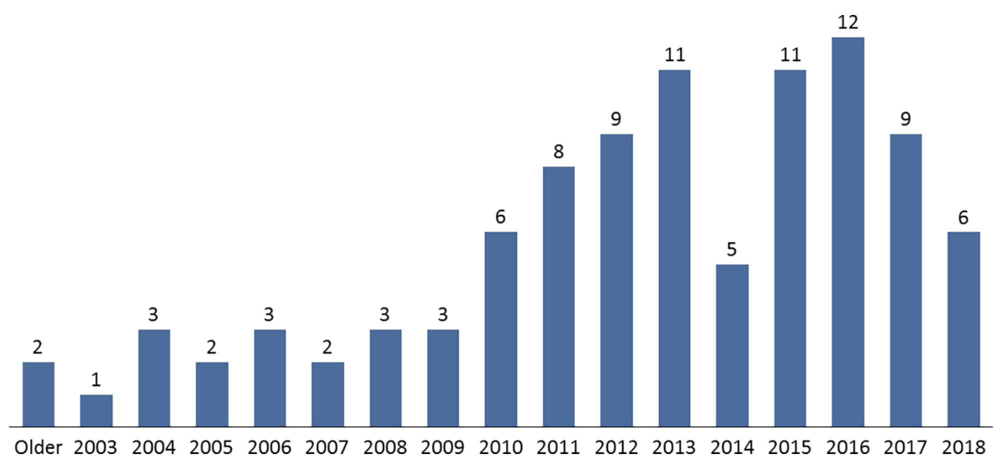

Fig. 3. Evolution of the literature publication dates. Note: Includes all studies in the scope of this article. No. for '2018' includes studies that were published until August 2018.

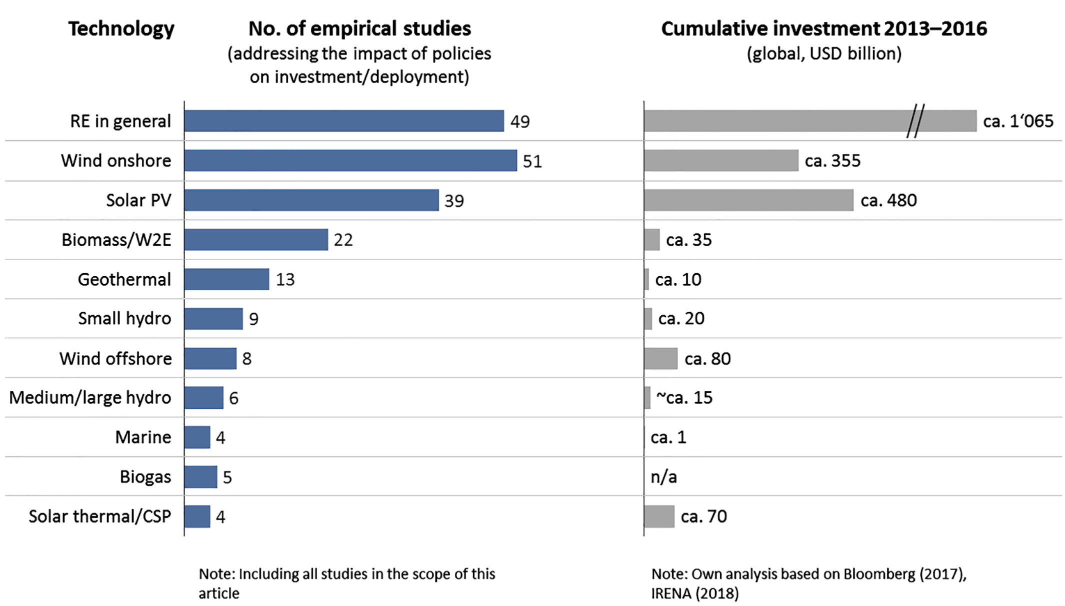

Fig. 4. Technologies covered with corresponding investment volumes.

Table 1
Taxonomy of instrument types with definitions.

Category	Sub-category	Instrument	Definition
Economic instruments		Public direct investment	Policies aimed at directly acquiring renewable power generation capacity by public authorities [cf. 75]
	Fiscal & financial	Feed-in tariff (FIT)	Policies offering a long-term agreement/regulation remunerating the sale of RE electricity at a fixed price which is typically above standard market levels [cf. 76]
		Feed-in premium	Policies providing a premium on top of regular market prices for the sale of RE electricity [cf. 75]
		Auction for PPA	Policies where public authorities organise tenders for a given quota of renewable supplies or capacity and remunerate winning bids at prices which are typically above standard market levels [cf. 75]
		Production tax credit/relief	Provides the investor or owner of qualifying asset with an annual income tax credit based on the amount of energy generated during the relevant year [cf. 2]
		Grants	Policies offering capital subsidies, consumer grants or rebates as one-time payments to cover a percentage of the capital cost of an RE investment [cf. 75]
		Subsidized investment loans/funds	Policies providing ad hoc subsidised financing for investors [cf. 75]
		Investment tax credit	Policies allowing for full or partial deduction from income tax obligations for investments in RE [cf. 75]
		Guarantees	Policies offering guarantees for private RE investors, e.g. purchase guarantees to assure that all generated electricity will be bought [cf. 77]
		Carbon tax	Tax on fossil fuels or carbon dioxide emissions intended to reduce the emission of carbon dioxide [cf. 76]
	Market-based	Carbon/GHG certificates	Policies introducing tradable carbon/GHG emission permits. Typically, the market size for these certificates is continuously being reduced (capped) [cf. 78]
		Green certificates	Policies introducing tradable RE certificates representing the certified generation of units of RE, allowing the trading of RE obligations among consumers and/or producers [cf. 75]
Other instruments	Regulation	Quotas/RE portfolio standards	Quantity-based policy requiring companies to increase the amount of power generated by RE. The mechanism obligates utility companies to generate a specified share of their electricity by RE. Tradable RE certificates may or may not be a part of the instrument [cf. 76]
		Net metering	Allows a two-way flow of electricity between the electricity distribution grid and customers with their own generation. The meter runs backwards when power is fed into the grid, with power compensated at the retail rate during the 'netting' cycle, regardless of whether instantaneous customer generation exceeds customer demand [cf. 2]
		Tech standards	Policies imposing standards on actors requiring them to undertake specific measures and/or report on specific information [cf. 73]
		Grid preference	Policies mandating that RE supplies are integrated into energy systems before supplies from other sources [cf. 2]
	Other	Long-term targets/ commitments	Steps in the ongoing process of developing, supporting and implementing policies, including targets and strategic plans, which guide policy development [cf. 73]
		Research, development and demonstration (RD&D)	Policies providing research, development and deployment support, such as grants or tax breaks [cf. 31]

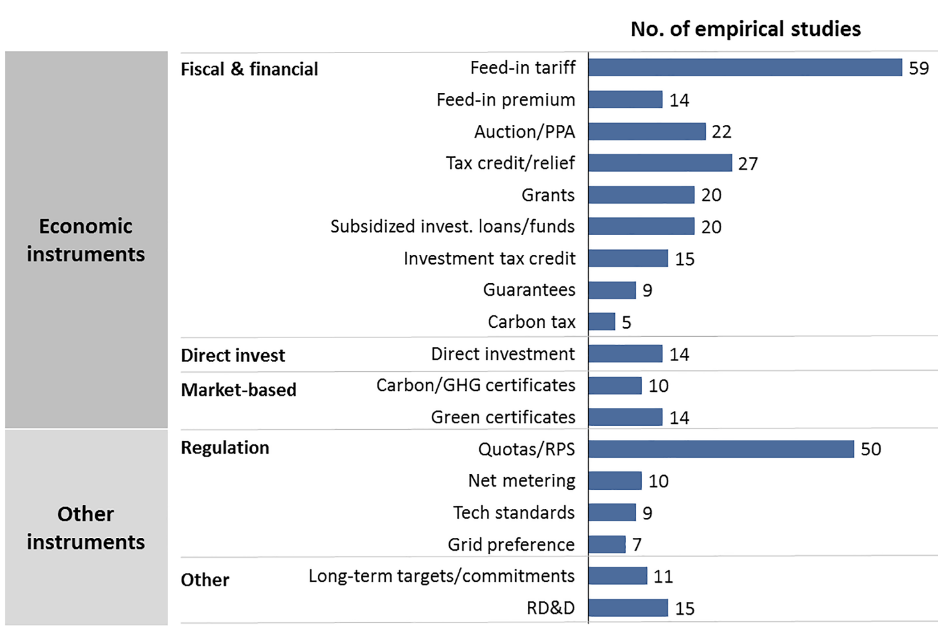

Fig. 5. Types of policy instruments.

5. Policy effectiveness through impact on risk and return of private investments

The empirical evidence concerning the effectiveness of different instruments, and particularly their impact on risk and return, is summarised in Table 2. In the following section we briefly describe the instruments' function and their most important impact channels on risk and return, using the four instrument sub-categories from Table 1. The narrative complements the tables by providing context on the actual use of different instruments, and by giving additional details concerning the evidence which is considered most important by the authors of this review.

Table 2
Policy effectiveness in inducing private investment through acting on risk and return.

Policy instrument		Overall instrument effectiveness[a]	Impact on risk	Impact on return
Public direct investment		Limited mixed evidence	No direct effect; indirectly helping to build technology track record	No direct effect
Fiscal & financial	Feed-in tariff	Mostly positive evidence; larger effect compared to other instruments; more suitable for less mature technologies; risk of over-subsidizing, might attract broader range of investors	If properly implemented, more effective in risk reduction than any other instrument; removes price risk, volume risk and balancing risk (no specific load profile needed); creates policy risk of retroactive changes	Ensures stable return over a guaranteed period; support level influences investor return, with stability and predictability often seen as more important than level of remuneration
	Feed-in premium	Limited positive evidence; could do well in combination with FIT; attracts investment in areas that can produce in peak hours and incentivizes smart load management, which benefits system stability	Weak link between risk and premium; revenue stability is likely better for emerging techs and smaller investors	Support level influences investor return; additional component of premium should attract more investment in sites which can produce in peak hours
	Auction for PPA	Mostly positive evidence, even attracts early stage finance; can be used to reveal real prices and bring prices closer to effective cost; auction volumes high but realisation volumes low; tenders can lead to favouring large projects	Depends largely on design (e.g. support duration, required pre-bid planning, penalties), thereby failing to reduce risk (especially for small projects)	Positive effect through fixed price; depends on design, e.g. banding and pricing (uniform vs. pay-as-bid vs. vickery vs. median); stability and predictability often seen as more important than remuneration
	Production tax credit/relief	Mostly positive evidence	High policy uncertainty	Reduction of property tax and sales tax directly affect return of projects
	Grants	Mixed evidence, positive for residential	No direct effect	Temporarily reduces financing cost for residential
	Subsidized investment loans/funds and investment tax credit	Mixed evidence	Guarantees reduce risk and, hence, reduce cost of debt	Public loans and funds generate financial resources; capital grants and tax deductibility of investment costs affect returns
	Guarantees	Limited mixed evidence	Guarantees reduce risk	No direct effect
	Carbon tax	Limited positive evidence	No direct effect	RE generates returns by selling certificates; reduces returns from carbon dioxide emitters
Market-based	Carbon/GHG certificates	Limited mixed evidence	No direct effect	Potential to indirectly affect returns by increasing cost for competing technologies
	Green certificates	Mostly positive evidence; low social cost in the short term, but rather negative effect (on technology diversity, etc.) in the long term	No direct effect	Additional return from sale of 'green value' of generated electricity
Regulation	Quotas/RE portfolio standards	Mixed evidence, mostly positive; differences according to technologies; effectiveness lags behind FIT; usually delivers below targets; generally cost-effective	Associated with regulatory uncertainty (targets) but not easily retractable; do not mitigate risk (price, volume and balancing risks remain); more equity financing by large incumbent firms, but price negotiations critical; additional income risk	Leads to larger and more cost-effective projects than FIT; affects returns of utilities; FIT and RE obligations provide above-market returns (around same levels); RE obligations act as a premium on top of the negotiated off-taker price in the PPA
	Net-metering	Limited positive evidence, especially for solar PV (US); does not work in the absence of dedicated and small-scale financing lines	Financing lines do not come from private market because they perceive net-metering as too risky	Improves the rate of return
	Tech standards	Limited positive evidence	Reduction in technology variety decreases risk of incompatibility existing energy system and technologies	Reduction in technology variety reduces costs
	Grid preference	Limited positive evidence	In some geographical contexts, crucial for risk; guaranteed grid access	No direct effect
Other	Information & education	Limited positive evidence	Information is linked to social acceptance, which lowers risk; education in financial sector can decrease risk by improving project appraisal/structuring	No direct effect
	Long-term targets/ commitments	Positive evidence	Planning certainty is conducive to investments	No direct effect
	RD&D	Positive evidence	No direct effect	Reduces cost of developing/ improving technology

[a] Limited evidence means that fewer than 10 papers cover the respective instrument.

5.1. Fiscal and financial instruments

Direct investment: Policymakers have the option to directly invest in a RE capacity [e.g. 14,29,71,79], for example, by using the vehicle of a green state investment bank [80]. While these investments do not directly mitigate risks for private co-investors, they can contribute to building a 'technology track record' and, thus, indirectly mitigate risks for the private sector [80].

FITs: FITs are the most widely implemented RE policy instrument globally, adopted by more than 80 countries by 2016 [17]. A large majority of the qualitative and quantitative studies associate the FIT with an increase in RE deployment and investment, and the effect is typically the largest of all the instruments, depending on the height of the tariff [e.g. 75,81–83]. A FIT reduces price risk for investors, as it guarantees a stable return over a specified period and caters well to the investors' need for predictable returns [31]. Consequently, FITs tend to lower financing costs [84]. Design elements, such as lead times, tariff durations, caps or grid connections, are often key success factors, as well [85,86] and are therefore discussed in detail in Section 6.

Feed-in premiums: There is less clear evidence for the effectiveness of feed-in premiums because they expose investors to the volatility of the electricity price to which the premium is linked [87–89]. While the effectiveness remains unclear, feed-in premiums create an incentive to balance the system and shave off peak load hours [87].

Auction for PPA: By 2016, around 30 countries worldwide adopted this support allocation mechanism [17], replacing FIT in some countries such as Germany [90]. Our reading of the evidence reveals mixed, but mostly positive, effects on RE deployment and investment [79,85,91–93]. Generally, auctioning volumes are good (i.e. high), but capacity additions usually remain below target because of the auction design [90]. The risk effect depends largely on design (e.g. support duration, required pre-bid planning and developer penalties) [94,95]. Similarly, the impact on return differs among designs (e.g. banding for specific technologies and auction pricing, contract standardisation and tariff caps) [18,90,94]. For a more elaborate discussion, see Section 6.

Production tax credits and tax relief: Approximately 40 countries worldwide include investment or production tax credits in their policy portfolio, and 100 countries reduce energy, sales, CO_2, VAT or other taxes [18]. We find mixed evidence for the effectiveness of production tax credits and reliefs [e.g. 96–100]. These instruments prove effective especially for biomass plants and wind turbine investments, as their generation costs have been historically closest to the market price and, hence, have the lowest profitability gap [92,97]. Property and sales tax incentives affect the return of RE investments. Generally, tax credits are associated with policy uncertainty since these directly depend on government budgets and changing fiscal decision making [101].

Grants: This basic form of RE support has been increasingly deployed over the last 10 years. Approximately 100 national jurisdictions feature public investment loans or grants [18]. The analysed literature reveals that grants can indeed spur RE deployment and investment. These forms of support are usually part of policy mixes including further fiscal and financial instruments such as FITs and tax breaks [71,72,102]. We find no direct effect on mitigating RE investment risk. Grants have been shown to have the greatest effect on increasing the return of a RE project in the residential segment by reducing upfront costs (not within the focus of this paper) in developed economies and, generally, in emerging economies [79,103,104].

Subsidized investment loans/funds and investment tax credits: These instruments, which feature prominently amongst energy policymakers, are weakly associated with mobilising private financial resources. Only a few studies find a positive effect [e.g. 72,102,105]. These investment-supporting instruments typically reduce the cost of debt (important especially for emerging economies), which increases equity investor returns. Tax deductibility of investment costs affects profitability [32], which is especially important for early-stage investors' return on equity [30,32].

Guarantees: In relation, studies provide some evidence that guarantees reduce risk for investors and, thus, accelerate the deployment of and investment in RE [e.g. 103,106,107]. Especially for novel technologies [79,80] and in emerging economies [27], this instrument has been proven to reduce risks. However, excessive loan guarantees for investors might lead to the funding of low quality projects and a resulting loss of investor confidence, which might explain part of the negative evidence [29].

Carbon tax: There is limited empirical support for the effects of explicit carbon pricing through a carbon tax. Eyraud et al. [31] found the strongest positive evidence, using RE investment microdata. Wall et al. [108] analysed the policy drivers for foreign direct investment (FDI) and found unanimous positive evidence. Other recent evidence is less clear-cut [109]. In a direct comparison of (fiscal) instruments, such as FITs or quotas by investors, the carbon tax is less preferred [30]. Interestingly, Pfeiffer and Mulder [91] found some effectiveness for CO_2 pricing mechanisms in Brazil, Russia, India, China and South Africa (BRICS). In general, a carbon tax is not considered to directly impact the risk of RE investments [30]; however, this instrument indirectly makes RE projects more attractive vis-à-vis their fossil fuel-based counterparts that are being affected. This is in line with one study which found that, to be effective, carbon taxes should be electricity-sector specific [109].

5.2. Market-based instruments

Emission trading scheme (ETS): Implementing a carbon emission cap-and-trade system (such as the EU ETS) to internalize the negative external effects of carbon emissions and induce low-carbon innovation and diffusion has been debated extensively among scholars [110–112]. Although theoretically optimal if stringently implemented globally, the direct empirical link between an ETS and RE deployment remains weak [76,111].

In the specific literature under consideration in this article, we find limited positive evidence for mobilising private finance and RE deployment [e.g. 29,76,113], especially as FDI in developing countries [108]. Even though it should have long-term implications if properly implemented, this is not reflected in our analysis due to the low prices of CO_2 certificates found globally, which, in turn, generate little incentives for individual investors [114]. At the same time, ETSs do not mitigate the risk of RE projects in light of investments in fossil fuel-based alternatives [13,29]. In some cases, mainly as a response to the newly induced risk (carbon price volatility), ETSs might lead to the postponing of RE investments [115]. Schmidt et al. [78] even found a perverse effect of ETS in inducing more coal rather than RE investment due to free allocations of emission certificates (grandfathering).

Green (RE) certificates: Another market-based instrument used in various countries is tradable green certificates for electricity produced from RE sources. Our analysis again reveals mixed evidence [e.g. 109,116–118]. Renewable energy certificates (RECs) depend strongly on (sub)national binding targets. We find only limited evidence linking the risks of RE projects to the development of green certificate markets [119].

5.3. Regulatory instruments

RPSs or quotas: RPSs and quotas have been employed in many jurisdictions and studied extensively [e.g. 120–125]. Approximately 100 jurisdictions worldwide, of which many are subnational states (e.g. in the US), introduced this instrument to support RE deployment [17]. The existing evidence is largely concentrated on the US [126] and the UK, with some additional insights from countries such as Sweden [127]. Generally, the use of RPSs/quotas is associated with the deployment of larger and more cost-effective projects owned by established companies and based on mature technologies, for example, landfill gas and wind onshore in the UK [128–131]. As they are mostly technology-neutral within the field of RE technologies [49], RPSs and quotas seem most effective when the underlying technologies are mature and potentially close to grid parity (for more details on technology-neutrality and other design features, see Section 6). RPSs often missed their stipulated deployment targets because price, volume and balancing risk remain, making revenues uncertain for investors [131,132]. Because RPSs favour mature (and more cost-effective) technologies, they tend to discourage the introduction of new technologies [122,133,134]. This is, in part, because the RPS does not mitigate revenue volatility (i.e. risk) and, therefore, favours incumbent firms with the capacity to finance projects on their balance sheet [135]. In emerging economies, technology-neutral quotas introduce additional income risk due to price competition among technologies and sites, as well as equity investors demanding a premium for it [85].

Net-metering: Net-metering, which has been adopted in more than 50 countries worldwide [17], often on a subnational level, has shown positive effects for the residential market [129,130], where it can improve the internal rate of return if dedicated financing lines are available. However, the investment size in this market segment is usually too small and risky for private financiers [101,120]. Consequently, Wall et al. [108] did not find an effect on attracting FDI. It would require the bundling of small projects into third-party ownership models, for example, through leasing them to house owners to attract professional investors [136].

Technology and grid standards: There are a number of technical regulatory instruments which have been studied in only a few papers. Standards such as grid codes, mandatory grid connection or reporting standards for produced electricity have been shown to only influence early stage investors [30]. They reduce the risk for technology incompatibility in the future and enable cost reduction by focusing on a limited set of technology specifications. Grid codes and grid preference, one of the design features of other instruments such as FITs, have proven to be important for reducing risks [27,85,137].

5.4. Other instruments

Information and education: These efforts can only indirectly influence private RE investments, for example, by establishing RE project evaluation standards in the investment community [80]. Allowing interest groups to take part in RE projects can increase social acceptance and decrease risk [138,139].

Long-term targets/commitments: Policy strategies such as long-term commitments (often operationalized through long-term targets) reveal mixed evidence, as they often depend on governmental credibility [29,72,140–142]. Trust in the future commitment of policymakers indirectly reduces the risk of investors and is one of the most important generic policy design features. Long-term strategies are particularly credible when coupled with a broad, non-partisan alignment [143], such as the German energy transition after 2011.

RD&D: Research, development and demonstration measures indirectly influence investments in RE technologies by reducing technical risk and decreasing costs. We find mixed evidence in our sample, especially for less mature technologies such as solar PV [93,109]. In China, Li et al. [96] associated wind power capacity additions to state RD&D programs.

To sum up the current state of knowledge on policy effectiveness in inducing private RE investment through reducing risk and/or increasing returns, we find that FIT (also in the early stages of the technology lifecycle), quota mechanisms and auctions (especially for mature technologies) tend to be the most effective instruments when used alongside a credible RE planning framework. However, the analysis reveals that identical instrument types can produce very diverse results. Our reading of the evidence points out that one needs to go one layer deeper and analyse policy design to draw meaningful conclusions about policy impacts on risk, return and its effectiveness. We therefore dedicate the following section to exploring policy design features and consider their impact on risk and return.

6. Policy design as determining factor of policy effectiveness

The consolidated evidence from our review points towards an important role of policy design in altering the risk and return of RE projects. For example, Shrimali and Jenner [144], Carley et al. [126] and Kilinc-Ata [92] all mentioned weak policy design and low policy *stringency* as reasons for ineffectiveness. Although few papers explicitly consider policy design in their analyses, many discuss near expiry and frequent policy revisions in relation to increasing risk of RE projects [e.g. 98,140]. In terms of design features, this refers to policy *predictability*. On the one hand, retroactive changes to existing policy regimes or changing renewable energy targets have a negative impact on effectiveness by reducing returns [e.g. 92,140]. For example, RPS policies had a significantly smaller effect in states which previously passed and repealed electric utility industry restructuring legislation [135]. On the other hand, iterative policy adaptation that builds on knowledge from past policy schemes and following market development (e.g. from technology availability to financing availability to grid and counterparty risk mitigation) keeps policy costs down [13]. In this regard, continuous monitoring, evaluation and coordination between responsible government bodies increase policy *credibility* and reduce legal risk, which better addresses investors' needs [145,146], underlining the importance of formal institutions [19].

Scholars recommend well-designed, technology-specific and credible policy set-ups (e.g. avoiding confusion between R&D funding and deployment) to increase effectiveness [86,138]. Prior research also recommends that adjustments to policies should only apply to future contracts, the timing should be known in advance and reflect market conditions and changes should not happen too frequently [86,94,147]. Sufficient lead times between announcement and implementation ensure that firms can adjust their operations and strategy [148]. Handling compliance with policy instruments flexibly seems particularly important if the market is competitive and electricity providers are not very solvent, as is the case in an emerging market with new players. Policy stringency, with clear contracts, seems to be even more relevant if the market is vertically integrated, for example, if the market is dominated by incumbent utilities [148]. Also standardized (long-term) contracts reduce overall legal risks [94,147].

In addition to these *generic* design characteristics of policy instruments, we analyse the *specific* policy design features of FIT, auctions and RPSs, the three most frequently implemented and analysed policy instruments, and their impact on the risk and return of RE projects.

6.1. FITs

Most FITs differentiate support levels (i.e. the tariffs paid) by technology. Consequently, we did not identify an empirical analysis of the influence of *technology-specificity* on RE diffusion [46,49]. We focus on the main design elements of a FIT, which include the duration of the contract, tariff level, premium, cap and grid connection (Table 3).

Tariff duration significantly influences the effectiveness of a FIT policy, as it guarantees revenue streams [15,109]. Hence, duration determines the riskiness of a project; a long-term contract reduces risk, whereas variability in duration increases risk [93,147].

Although many studies find a positive effect from the *tariff level* on diffusion and investments of RE in general [82,149,150], other analyses differentiate this pattern according to technologies and type of investor [151,152]. For example, Cárdenas Rodríguez et al. [97] included the tariff level for wind and PV project investments globally and found a positive effect. However, excessively generous FITs, especially in the solar PV sector, discourage investments, as investors are concerned about the sustainability of such a regime [75,97].

A *fixed tariff* has been found to reduce or remove the price risk completely, therefore affecting the return on investment [82,153,154], whereas variability of the tariff structure increases uncertainty [82,93,154]. For example, when the German FIT was revised from a premium to a guaranteed price in 2000, it became evident that the FIT was valid irrespective of the timing and volume of electricity provided. These design parameters transferred price, as well as volume and balancing risk (through priority dispatch), away from the generator onto the grid operator [155]. If a FIT is implemented as a *premium,* it makes the policy less attractive than a fixed price, due to the remaining electricity price risk [147], but still positively

Table 3
Instrument design and effects on risk/return for FITs.

	Effectiveness	Risk	Return
Duration	Contract duration and price have significant influence on the effectiveness of FIT [15]	Contract duration impacts risk [15,82,109]; long-term contracts reduce revenue risks [147]; variability of duration and cap increases uncertainty [93]	Tariffs weighted with the duration of PPAs have a positive effect on RE investments [109]
Tariff level	High tariffs might also negatively affect deployment [15,82]; excessively generous FITs tend to discourage investment [75,97]; only some models find positive effects from tariffs [150]; FIT stability is often mentioned, but changes do not distract investors [158]	More variability in tariff increases uncertainty [93]; FIT reduces/removes all risk [138,153]	FIT linked to return [82,149]; stability of regulation (volume and price) is important [154]; FIT based on generation cost instead of being value-based can mobilize investment [147]
Premium	Positive effect on ratio between the FIT and the retail electricity price [156]	Premium riskier than fixed FIT [147]	Premium component crucial for affecting return [153]
Cap	Negative evidence [93]	Cap of FIT can cause uncertainty amongst potential investors [93]; governing mechanisms should be clear [147]	Caps make policy cost more predictable and increase bidding competition, thus lowering price [82,94]; planned digression favourable [82,153]
Grid connection	Guaranteed grid access makes FIT effective [85]	Grid connections (swift grid access) and dispatch decrease risk [138,147,154]; anticipatory grid planning also reduces risk [157]	Low pass-through of interconnection fee affects return and increases deployment [157]
Design other		Standard contracts decrease legal risks [94,147]; long-term contracts reduce revenue risks [147]; FITs that purchase less than 100% of the generated volume are riskier [147]	

affects the return [153,156]. Also, those FITs that take into account on-site consumption are riskier because on-site consumption is typically not secured by a contract [147].

Capping a FIT can take two forms: policymakers could choose to limit the amount spent on RE electricity in total (*absolute cap*), or they could limit the price the ratepayer bears as a consequence of the FIT *(ratepayer impact cap)*. The absolute capacity eligible for a FIT reduces the total costs of the policy and increases the policy cost transparency with regard to the taxpayer [94]. However, such a cap induces significant risks and uncertainty in investors' calculations as it is unclear whether the individual project falls under the cap or not [93]. To mitigate these risks, transparency regarding the governing mechanism of caps is required. Also, absolute caps might be clearer than a ratepayer impact cap that may need to be translated into eligible capacity additions [147]. An alternative proposed in the literature is to plan the digression of the FIT ahead and make it adaptable in a predictable way [153], for example, it is suggested to base digression on the previous year's deployment, as shown by the flexible cap regulation in Germany since 2012 [143].

Guaranteed grid connection and dispatch have been found to be of the utmost importance for a successful FIT, reducing project risk [154], especially in emerging economies [85]. Lowering the pass-through of the interconnection cost of grid operators to project owners can further increase deployment by lowering the project costs [157].

6.2. Auction for PPAs

Together with its recently growing implementation, several design variants of auctions have emerged (see Table 4). These flexible deployment options include different contract durations, bidding

Table 4
Instrument design and effects on risk/return for auction for PPAs.

	Effectiveness	Risk	Return
Duration	Needs to last long enough to be effective [139]	PPA duration a determinant of risk [109]; PPAs mitigate market risk (long-term contracts) [159]	
Price	Starting off with a high price can attract sufficient investment [94]; uniform pricing (and high competition) can lead to strategic (low) bidding and low realization; pay-as-bid is more robust against strategic bidding than uniform pricing [90]	Pricing/tariff mechanisms (e.g. guaranteed prices) address risk [159]; lowest price bids increase the concentration of RE power plants [139]; risks too high for new entrants [90]	Stable prices (i.e. revenues) are more important than the level of remuneration [94]; returns usually lower than FIT [90]
Banding	Banding makes the policy technology-specific [90], but it might result in administrative costs and low competition within bands [139]		Many bands can lead to low competition per compartment (see effectiveness) and, thus, higher returns [139]
Set-up of bidding rounds		Stop and go difficult for planning [139]; monitoring and evaluation is according to transparent criteria (risk) and requires secured debt pre-bidding to lower project risk [94]	Uniform set-up for all auctions favours industry learning and, hence, lowers financing costs [94]
Volume caps		Caps make policy cost predictable and can, thus, make the policy more credible (especially in emerging economies) and lower risk [94]	Caps increase bidding competition and can, therefore, lower prices [94]
Contract specification	Penalty for non-performance or non-construction increases effectiveness [139]; no pre-bid building permit lowers realization rate; non-price selection criteria increase diversity [90]	Standardized contracts reduce risk [94]; penalties and pre-bid requirements increase risk, especially for small developers [90]	Penalties can also increase revenues by increasing risk and, thus, decreasing competition [90]
Technology specificity	Tech neutrality provides few opportunities for immature techs; [90]		Highest profit for lowest cost technology results in low tech diversity; technology neutrality reduces revenues by increasing competition [90]

processes and pricing, but regardless of the design options chosen, a uniform set-up for all auctions favours industry learning and, therefore, increases policy effectiveness [139].

The first determinant of policy effectiveness is the *duration of the PPA/contract*, which investors/project developers are bidding for. Longer durations reduce project and financing risks significantly as longer stable cashflows are preferred by debt providers [109,159]. Second, the *pricing mechanisms* of an auction matter. Strategic bidding by the developers may result in construction delays or even projects being abandoned [139]. On the one hand, starting off with a high price seems necessary to attract sufficient investment [94]. On the other, selecting the lowest priced bids can increase the geographic concentration of RE power plants, as project developers build bigger installations to reach cost targets, therefore, increasing the likelihood of social resistance [139]. Mora et al. [90] explored the pricing dynamics in auction systems in 13 countries and found that uniform pricing (and high competition) can lead to strategic (low) bidding and low realization rates, as was the case in Spain. Finally, if an auction mechanism is used in combination with other policy support measures, it can be an efficient means to determine the required price, for example, the level of the FIT [77]. Additionally, streamlined planning procedures and low pre-auction requirements lower risk since they reduce legal complexity [139].

Scholars find that the risks of auctions might be too high for new entrants, as they typically incur higher financing costs and lack the advantage of 'economies of scale', which can be seen for example, in the context of Brazil [90]. Returns in auction mechanisms are usually lower than in a FIT, unless competition is very low because of design flaws. For example, in France, requirements for auctions were badly communicated; subsequently, most bids were invalid. In Denmark, very high penalties for offshore wind projects discouraged investors from bidding [90].

Moreover, research points out that *banding* assigns specific price-ranges and premiums to less mature technologies, as the price can be technology-specific. However, the excessive use of bands results in high administrative costs and low competition within the bands assuming the same overall number of investors (i.e. higher returns for investors) and, thus, lower effectiveness [90]. Technology-neutral auctions offer no chance for less mature technologies. However, a lower technological diversity also reduces the short-term (administrative) costs of the policy measure [90].

Auctions can also be arranged in *bidding rounds*, but sporadic stop and go, as well as a difficult planning process (e.g. pre-bid permissions), increases risk [139]. Organising the monitoring and evaluation of bidding rounds according to transparent predefined criteria can reduce risks. Requiring secured debt before entering the bidding process forces banks to use due diligence, therefore lowering project risk for (equity) investors in the project [94]. However, requiring additional pre-bid permissions increases the risk for project developers who have to invest to get the permission, as they may end up not getting the project [90,139].

Another design element of auctions is the *volume caps*. These make the policy cost predictable and the policy more credible as a result (especially in emerging economies), which lowers policy reversal risk. Caps also increase bidding competition and can, as a result, lower auction prices [94].

Finally, *contract specification* plays an important role in designing the auction mechanism. Including non-price selection criteria, such as social responsibility or actor diversity, can help to achieve policy goals other than deployment, as demonstrated in the case of South Africa [90]. The UK, for example, reduced the risk for small developers by limiting developers to only one awarded contract. In the Netherlands, small developers are exempt from pre-bid requirements [90].

6.3. Quotas/RE portfolio standards

Our literature review (Section 5) revealed that the effect of renewable portfolio standards (RPSs) on subsequent investments in RE capacity depends on the stringency and implemented design. Carley et al. [126] recently developed a measure for RPS stringency that encompasses the amount of renewable energy required over the number of years that policy is in place. They find that more stringency favours RE and solar PV generation. Interestingly, more stringent RPSs are not, however, conducive to more wind energy being generated.

RPS can be further customized in many ways, for example, by adjusting the duration of the contract, by defining capacity or sales requirements (including nominal vs. incremental capacity), by favouring less mature technologies that strategically use banding (price measure) or carve-outs (volume measure) or by introducing penalties. Other influencing factors include the percentage mandate, mandatory vs. voluntary RPSs and the number of years the policy has been present (see Table 5).

First of all, similar to FITs, *contract duration* plays a major role for the effectiveness of a RPS, as it signals policy stability [105] and, as a result, reduces policy risk. For example, an analysis of British RPSs revealed that short contract durations meant that RE producers and, consequently, investors would be undercut a few years down the road by new plants [12]. Governments that guarantee returns in a RPS contract if the utility fails to pay can be a remedy to this risk [126,144]. More recent evidence finds that RPS duration does not have an effect on wind capacity; therefore, RPS design might not impact investor confidence in this policy [15,126].

Second, scholars looked at the distinction between capacity requirements and sales requirements. Depending on the type of RPS, Shrimali and Kniefel [79] found different effects on the installed solar, wind and biomass capacity in the US. These results also depended on the specific RE policy in the respective US state. In both cases, guaranteed headroom between projected RE generation or sales and required certificates make certificate price collapses less likely and, therefore, reduce investment risk [131].

Third, studies distinguish between *nominal* required capacity in a RPS and *incremental* additions based on previous years [122]. Whereas some studies have found the former to be effective, especially in high-income countries [104], others found no effect [15]. In a direct comparison, those RPSs that require incremental capacity additions outperform those with nominal capacity requirements because these might already be met when the policy is introduced [122].

Fourth, assigning more certificates (for example via a multiplier) to certain technologies (*banding*) ensures technological diversity [105], reduces risk for corresponding investors and provides revenues [160]. Banding can thus help less mature technologies enter the market, attract investors [131] and avoid excessive subsidies for mature low-cost RE technologies [160]. Another possibility to deploy banding could be to set the multiplier rate (the relation between certificates and capacity) according to technologies by a government instead of by market participants [160].

Fifth, *carve-outs* mandate part of the RPS target be matched by defined (high-cost) technology, which allows for the entry of less mature RE technologies [160]. On the one hand, this design feature delivers a predictable number of certificates. On the other, it splits the RE certificate market, which might create liquidity issues, if there are low trade

Table 5
Instrument design and effects on risk/return for RPSs.

	Effectiveness	Risk	Return
Duration	Purchase requirements must increase over time [148]	Policy duration uncertainty affects risk [161]; long-term contracts reduce risk of being undercut by new plants [12]; duration does not impact investor confidence [15]	Contracting mechanisms; state can provide guaranteed financial return for RE [129]
Capacity vs. sales	RPSs with capacity requirement conducive for geothermal, not for wind; RPSs with sales requirements conducive for solar and geothermal, not for RE in general or biomass plants [129]	Guaranteed headroom for capacity or sales between projected RE generation and required certificates reduces price risk [131]	
Nominal capacity vs. incremental capacity	Higher effectiveness for RPS than FIT for high-income countries [16]; quota award rate has no effect [15]; nominal RPS negatively correlated with share RE; incremental RPS positively correlated with share RE [122]	RPS mitigates risk (non-easily retractable measure) [29]; maximum effective retail rate increase (MERRI) after accounting for price caps of the penalty (alternative compliance payments) reduces risk [129]	
Banding (price measure)	Specific resource bands can help to diversify technology deployment [148]	Does not split up certificate market [160]; more certificates per megawatt hour (MWh) or different multiplier rates [160] for less mature technologies lowers the risk [131]	No over-subsidisation of low-cost technologies; drives RE cost reductions [160]
Carve-outs (volume measure)	Delivers predictable amount of RE [160]	Splits up certificate market (liquidity issues) [160]; creates boom and bust cycle if RE generation of a technology nears carve-out, and certificate prices will plummet [160]	Markets set differential among technology prices [160]
Penalties	Increase policy credibility [148]	Enforcement should be strict and clear (e.g. automatic financial penalties in case of non-compliance) [148]	
Design other	Number of years a RPS has been enacted positively influences utility share of RE investments of total investments (wind, solar) [121,126]; RPS that allows non-renewable energy generation negatively affect Solar generation and RE generation; RPS percentage mandate and mandatory increases share of RE, Solar generation and RE generation; RPS cost recovery increases share of RE, RE generation; RPS planning activities positively affects share of RE, Solar generation and RE generation; RPS geographical limits increase share of RE, Wind generation; REC markets positively affect Wind generation [126]	FIT for less than 5 Megawatts projects: smaller projects would seldom benefit from RPS, as the transaction costs and investment risks are too high [131]	Most cost-effective RPS solution, which reduces return for utilities [122]

volumes, and may lead to a boom and bust cycle, if the carved-out capacity limit is approaching [160].

Sixth, scholars found that *penalties* for non-compliance with the RPS are only partially effective [126]. The scheme needs to be strictly enforced and in a timely manner in order to make the policy effective [148].

Finally, a recent mixed methods study by Carley et al. [126] included a range of other factors influencing the effectiveness, such as the percentage mandate, RPS mandatory policy, potential cost recovery for the utility and the number of years the policy has been present [see also 121,135]. Their study mostly found positive effects of an increase of RE and solar generation for many of these options. If trading of obligations is allowed, the additional exposure to the certificate market, with its multiple contracts and counterparties, introduces further risk. Higher RE targets and guaranteed headroom between projected RE generation and required RE capacity can reduce the risk of a price collapse and, therefore, increase investment [131]. In addition, Carley et al. [126] showed that tradability of generated certificates and the geographical limits in which they can be traded increases wind energy generation.

7. Conclusions and implications

7.1. Synthesis of the findings

In this paper, we set out to systematically review the empirical qualitative and quantitative literature on the influence of policy measures on RE deployment and investment. We specifically explored the mechanisms that link investment risk and return to the effectiveness of the instruments. We detected several interesting patterns that have received little attention hitherto. For instance, we observed that instruments that reduce risk and provide high certainty for investors are particularly effective in triggering private investment. Often, these instruments address the return metric as well. At the same time, our reading of the evidence suggested that the type of policy instrument only matters partially in the mobilisation of private finance for the deployment of RE technologies. Without paying special attention to policy design characteristics and implementation, which affect risks, policymakers and academics alike risk missing the *actual* determinants of effectiveness.

Our review of empirical literature underlines the high potential effectiveness of FITs and RPSs in attracting private investors, especially in comparison to other fiscal/financial, regulatory or market-based instrument types, such as carbon or green certificates. FIT performs better than any other instrument with regards to the introduction of new technologies. However, this comes at a cost, namely, uncertainty over the policy cost and a higher cost compared to a policy that always supports the marginally most cost-efficient technology. For all policy instruments, our review highlights credibility (no-retroactive changes) as a key design feature. In addition, continuous evaluation and monitoring to reflect market conditions minimises policy cost which also reduces the risk of (retroactive) policy dismantling. Additional aspects that might matter for policy credibility include how different instruments overlap to assure investors that their investments will remain profitable even if one of the instruments is removed [146].

The review of specific policy design options of FIT, auctions and RPSs reveals the fundamental trade-off between technology specificity offering favourable conditions (and higher returns) to less mature technologies and technology neutrality ensuring the deployment of the currently most cost-efficient technology. While the former increases technology diversity, it also increases the cost of the policy measure. If deployment/volume caps are introduced to ensure policy costs remain manageable, mechanisms and lead times should be transparently communicated to avoid negative effects on projected returns and calculated risks. Above all, standardized procedures and common design elements of policy instruments enable investors to gain experience more quickly and, consequently, reduce the risk in RE projects.

Our analysis of the empirical literature also emphasises the fact that many of the findings and results obtained are technology- and context-specific, which is in line with other analyses [e.g. 18]. Accordingly, more differentiated results, including the geographic scope of each respective study, are provided in Tables A.1 and A.2 in Appendix A.

7.2. Implications for policy

There are a number of policy implications generated from our work, and our study supports the decision-making process of policymakers in choosing instruments and design parameters.

In general, to ensure the effectiveness of policy instruments in attracting private investors, policymakers need to take the risk and return dimensions into account when considering the choice and the design of policy instruments. A first implication relates to technology-specificity, i.e. whether support levels are specific for different technologies. A high technology specificity seems to be particularly relevant for less mature technologies, which require higher *return* levels to compensate for the risk due to the missing track record. In other words, leaving the technology selection to the market will result in the most mature technology being selected. In order to avoid picking a technology with potentially low prospects, a portfolio approach focusing on several technologies can be taken. This, however, is likely to result in increased cost.

Second, the risk and return dimension should be taken into account also for policies supporting mature technologies, a status that solar PV and onshore wind have achieved in investment grade countries. Increasingly, policymakers move towards auctioned PPAs or market premiums for these technologies which require calibrations on many design parameters, as illustrated in this review. Explicitly considering the impact on risk and return of each parameter can help to design effective schemes and should likewise guide researchers who advise policymakers in that regard.

Third, reducing policy cost can be achieved through reducing *political risks*, which, in turn, lower financing cost. Policy predictability or stability is important in reducing risk. The basis for that seems to be a long-term strategy with a low risk of policy dismantling. At the same time, technological change requires some degree of flexibility in the policy, which must be adapted to falling RE cost. To avoid a trade-off between predictability and flexibility, policy adjustments should be announced early and be reasonable (i.e. reflect actual cost reductions). An alternative approach consists of 'adjustment rules' that specify under which (predetermined) conditions the government is allowed to deviate from existing policies [162]. There are ways to ensure that less mature RE technologies, such as solar PV (in the early 2000s), geothermal (in the early 2010s) or tidal (in 2018+), can be 'phased-in.' Design elements that favour such a phase-in include technology-specific FITs, RPSs with banding or carve-outs or auction regimes with technology-specific banding. Common to all instruments, international coordination would help to reduce technology costs more efficiently while maintaining stable electricity prices.

Finally, as renewables mature, a debate around phasing out support policies is emerging [163]. Our findings also have implications for this debate. Instead of completely abandoning policy support, which could deter investors, a gradual shift from more to less stringent policy designs seems more promising. Moving from one instrument type to another is also an option. Understanding investor decisions and risk perceptions will be crucial for policymakers in order to not lose private investment volumes when phasing out or shifting public support schemes.

7.3. Limitations and implications for research

This literature review specifically focuses on the implications of RE support policies (instrument choice and design features) for risk and return perceptions of RE investors in the deployment of RE. Avenues for future research broaden the scope of our research in five ways: First, this literature review provides the starting point for exploring more policy design options and their risk and return levers. Scholars could also disentangle the effects of instrument type and stringency, which this review has not done. Until now, measuring the stringency of a policy's instruments has proven a complex endeavour [126,135]. Second, subsequent research could broaden the spectrum of policy assessment, for example, by also considering private investments in energy efficient technologies or innovation. Third, scholars should explore the risk/return preferences of RE investors over time to verify some of the findings of this report and link them to conceptual or model evidence [164,165]. Fourth, in a response to potential unintended (or counteracting) consequences of different sets of policies, the policy mix literature stream [50,166,167] could be extended to include risk and return considerations. Finally, one should consider the socio-economic impacts of supporting different kinds of investors (professional, community, household, etc.), especially regarding inequality, energy justice or social acceptance [6,59,168,169].

Acknowledgements

This research was conducted as part of the EU's Horizon 2020 research and innovation programme project INNOPATHS under grant agreement No. 730403. As such, it was partly supported by the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract number 16.0222. The opinions expressed and arguments employed herein do not necessarily reflect the official views of the Swiss Government. The author team is grateful for comments on early versions of this paper, presented at the INNOPATHS finance stakeholder workshop in Utrecht (September 2017), at the project meeting in Florence (February 2018) and at the 6th International Symposium on Environment and Energy Finance Issues (ISEFI) in Paris (May 2018).

Appendix A

Table A1
Policy influence on financing renewable energy (quantitative or mixed methods).

Citation	Geogr. scope	Tech. scope	Economic instruments												Other instruments						
			Fiscal & financial instruments									Market-based Inst.		DI	Regulations				LTT	RD&D	Other
			FIT	FiP	Auct.	Tax cr.	Grant	Loan	ITC	Guar	C tax	ETS	GCE		RPS	NM	TS	GP			
Polzin et al. [29]	OECD, 27 countries	RES	+			+	●	●	●	●		+	●	–	+				+		
		Wind	+			●	●	●	●	●		+	●	●	+				●		
		PV	+			+	+	–	●	●		–	–	–	+				+		
		Bio	●			●	●	●	●	●		●	●	±	●				–		
García-Álvarez [15]	EU, 28 countries	Wind	+												●						
Ang, Röttgers and Burli [109]	OECD + G20, 46 countries	RES	+	●	●						(+)		●							●	
		Wind	●	●	+						●		+							+	
		PV	+	●	●						+		+							–	
Romano et al. [32]	Global, 56 countries	RES	–			+	●	●	+				+	●	–	+					
Aguirre and Ibikunle [71]	EU, OECD, BRICS, 38 countries	RES	+	●	●	–	–	●	●	●		●	●	●	●					●	
Cárdenas-Rodríguez et al. [97]	Global, 87 countries	RES	±			±									±					●	
		Wind	(+)			(+)									(+)					●	
		PV	(+)			●									–					●	
		Bio	+			(+)									●					+	
		SHP	–			●									+					–	
Carley et al. [104]	Global, 164 countries	RES	(+)				●								(+)				●		
Eyraud et al. [31]	Global, 35 countries	RES	+								+	+			●					●	
Nicolini and Tavoni [150]	FR, IT, GB, DE, ES	Wind, PV, Geo, SH, M/LHP	+										–								
Criscuolo and Menon [75]	OECD + EMDC, 29 countries	RES	●		+								●		+					+	
		Wind	+		+								●		+					+	
		PV	±		+								●		+					+	
Baldwin et al. [170]	Global, 149 countries	RES	+				+								+				●		
Kim and Park [116]	Global, 30 countries	RES (Wind, PV, Bio, Geo)	+										+							●	
Bolkesjoe et al. [149]	EU, 5 countries	Wind	+		●										●						
		PV	+		●										●						
		Bio	●		●										+						
Cumming et al. [171]	Industria-lized, 31 countries	RES																			±
Eleftheriadis and Anagnostopoulou [140]	GR	Wind	●			●												●	●		
		PV	●			●												●	●		
Marques and Fuinhas [72]	EU, 23 countries	RES	+	+	+	+	+	+	+	+									●		
Marques and Fuinhas [142]	EU, 21 countries	RES																			±
Bird et al. [105]	US, 12 states	Wind				+	+	+	+				●		+				●		
Delmas and Montes-Sancho [127]	US, 48 states	RES													±						

(continued on next page)

Table A1 (*continued*)

Citation	Geogr. scope	Tech. scope	Economic instruments												Other instruments						
			Fiscal & financial instruments								Market-based Inst.			DI	Regulations				LTT	RD&D	Other
			FIT	FiP	Auct.	Tax cr.	Grant	Loan	ITC	Guar	C tax	ETS	GCE		RPS	NM	TS	GP			
Johnstone et al. [107]	OECD, 25 countries	RES	●			●	+	+	+	+			●							+	
		Wind	–			●	●	●	●	●			●							+	
		PV	+			●	●	●	●	●			●							+	
		Bio	●			●	+	+	+	+			●							●	
		Geo	●			●	+	+	+	+			●							+	
		Marine	●			●	●	●	●	●			●							●	
Menz and Vachon [124]	US, 39 states	Wind													+						
Jenner et al. [82]	EU, 26 countries	Wind	+	●	●	●	●														
		PV	+	●	●	●	●														
Popp et al. [151]	OECD, 26 countries	Wind	●												●						
		Bio	+												●						
Schmidt et al. [141]	EU, 7 countries	Other										±									
Schmidt et al. [78]	EU, 7 countries	Other										●									
Cansino et al. [99]	EU, 27 countries	RES				●			●												
Fabrizio [135]	US, 49 states	RES (Wind, PV, Bio, Geo, Other													●						
Pfeiffer and Mulder [91]	Global, 108 countries	RES (Wind, PV, Bio, Geo)	+	+	+	+	+	+	+	+	+	+	+	●	+	+	+	+	–		
Chang et al. [98]	Asia, 16 countries	RES	●	●	●	●		●					●	●	●	●	●		●	●	
Brunnschweiler [70]	Non-OECD, 119 countries	RES (Wind, PV, Geo, SHP, M/LHP)																			+/-
Shen and Luo [103]	CN	RES (Wind, Solar, Bio, Other)	●	●	●	●	●	●	●	●				●				●			
Linnerud and Holden [117]	NO	SHP											●					–			
		MLHP											●								
Barradale [159]	US	Wind			–	–			●												
Kilinc-Ata [92]	EU, 27 countries + US, 50 states	RES	+		+	+									●						
Shrimali et al. [129]	US, 51 states	RES						●							+	+					
Carley [161]	US, 39 states	RES													+						
Shrimali and Jenner [144]	US, 16 states	PV				+	+								–	●	●				
Shrimali and Kniefel [79]	US, 50 states	RES			●		+							●	–						
		Wind			●		(+)							●	(–)						
		PV			●		●							●	●						
		Bio			●		+							●	±						
		Geo			●		(+)							●	●						
Bürer and Wüstenhagen [30]	60 principal or senior fund mangers	RES	+			●	+	+			●	●	●		●		+			+	
del Río and Tarancon [81]	EU, 27 countries	Wind	+																		
Dong [133]	Global, 53 countries	Wind	+												●						
Krasko and Doris [130]	US, 51 states	PV													+	+					
Li et al. [96]	EU, 21 countries	Wind	+			+	+	+							+					+	
		PV	+			●	●	●							●					●	
Sarzynski et al. [101]	US	PV				+	+								+	●					
Schmid [125]	IN, 9 states	RES	●												+						
Smith and Urpelainen [83]	Global, 26 countries	RES (Wind, PV, Bio, Geo)	+																		
Yin and Powers [122]	US, 50 states	RES						●							+	●					

(*continued on next page*)

Table A1 (*continued*)

Citation	Geogr. scope	Tech. scope	Economic instruments												Other instruments						
			Fiscal & financial instruments									Market-based Inst.		DI	Regulations				LTT	RD&D	Other
			FIT	FiP	Auct.	Tax cr.	Grant	Loan	ITC	Guar	C tax	ETS	GCE		RPS	NM	TS	GP			
Kahn [100]	US	Wind				+															
Gavard [88]	DK	Wind	+	+																	
Mulder [102]	EU, 15 countries	Wind	+			+	+	+													
Dijkgraaf et al. [93]	OECD, 30 countries	PV	+												●					●	
Choi and Anadon [156]	OECD, 14 countries	PV	+												+					●	
Weigelt and Shittu [121]	1542 firms	RES				●									+						
		Wind				●									+						
		PV				●									+						
		Bio				●									●						
Carley et al. [126]	US, 51 states	RES													+						
		Wind													–						
		PV													+						
Wall et al. [108]	Global, 137 countries	RES	+		+	+	●		–		+	●	●		●	●					+
		Wind	+		●	●	●		–		+	+	●		+	●					+
		PV	+		+	●	●		+		+	●	●		+	●					●
		Biomass	+		●	+	●		–		+	●	–		●	–					●
Best and Burke [113]	EU, 28 countries + Global, 139 countries	Solar PV	+									+									+
		Solar thermal	+									+									+
		Wind										+	–								

FIT = Feed-in-tariff, FiP = Feed-in-premium, Auct. = Auction/PPA, Tax cr. = Production tax credit/relief, Grant = Grants, Loan = Subsidized investment loan/funds, ITC = Investment tax credit, Guar = Guarantees, C tax = Carbon tax, ETS = Emission trading scheme, GCE = Green certificates, DI = Direct investment, RPS = Quotas/RE portfolio standards, NM = Net metering, TS = Technical Standards, GP = Grid Preference, LTT = Long-term targets/commitments, RD&D = Research Development and Demonstration, RES = Renewable Energy Systems in general, Wind = Onshore and Offshore Wind, PV = Photovoltaics, ST = Solar Thermal Energy, Bio = Biomass and Waste-to-Energy, Geo = Geothermal Energy, SHP = Small Hydro Power, M/LHP = Medium and Large Hydro Power, Marine = Marine Energy, Other = Other

+ = positive, - = negative, ± = positive and negative, ● = considered in paper, no instrument effect specified, [blank] = not considered in paper.

(*) = Paper does not (or sparsely) evaluate policy effects, but discusses design elements, circumstantial effects or others in detail.

Table A2
Policy influence on financing renewable energy (qualitative methods).

Citation	Geogr. scope	Tech. scope	Economic instruments												Other instruments						
			Fiscal & financial instruments								Market-based Inst.			DI	Regulations				LTT	RD&D	Other
			FIT	FiP	Auct.	Tax cr.	Grant	Loan	ITC	Guar	C tax	ETS	GCE		RPS	NM	TS	GP			
Friebe et al. [85]	EMDC	Wind	+		●				●						●			+			
Butler and Neuhoff [132]	GB, DE	Wind	+		●																
Mitchell et al. [155]	DE, GB (England, Wales)	RES	+	+											(+)						
Jacobsson and Lauber [167] (*)	DE	RES	●	●											●		●		●	●	
Mignon and Bergek [19] (*)	SE	RES																			
Anadon and Surana [13] (*)	CN, IN	Wind	(+)			(+)								+	(+)						
Lipp [138]	DK, DE, GB	RES	+												(+)						
Mitchell and Connor [128]	GB	RES													(+)						
Heiskanen et al. [152]	FI	Wind	+																		
		PV	●																		
		Bio	●																		
		Geo	●																		
		Other	●																		
Shrimali et al. [120]	IN	Wind	+					+				(+)						+			
		PV	+					+				(+)						+			
Holburn [145] (*)	Ontario, Texas	RES																			
Bergek and Jacobsson [134]	SE	RES													+						
Menanteau et al. [9]	Europe	Wind	+												(+)						
Sovacool [137]	BE, CA, DK, FR, DE, JP, KR, PH, SG, ES, CH, GB, US	RES	+			●	●	●	●						●	●	●	●		●	
Peña et al. [153]	PT	Wind	(+)																		
Becker and Fischer [77]	CN, IN, ZA	PV	●		●																
Leete et al. [118]	GB	Marine													(+)						
del Río and Unruh [172]	ES	Wind	●	●																	+
		PV	+	●																	
Gutermuth [106]	DE	Wind	●	+			●	+	●	●											
		PV	●	(+)			+	●	●	●											
		Bio	●	(+)			+	+	(+)	●											
		Geo	●	●			●	+	●	●											
		M/LHP	●	+			●	+	+	●											
Jacobs et al. [147] (*)	Latin America and Caribbean	RES	●																		
Yoon and Sim [86] (*)	KR	RES	●												●						
del Río and Gual [154] (*)	ES	Wind, PV, ST, Bio, SHP	●	●																	
Fouquet and Johansson [158]	GB, DE	RES	+												(+)						
Alagappan et al. [157]	US	RES	+												(+)			+	+		
Eberhard and Kåberger [94]	ZA	Wind	●		+																
		PV	●		+																
		ST	●		+																
		Bio	●		●																
		M/LHP	●		●																
Woodman and Mitchell [131]	GB	RES													(+)						

(continued on next page)

Table A2 (*continued*)

Citation	Geogr. scope	Tech. scope	Economic instruments												Other instruments						
			Fiscal & financial instruments									Market-based Inst.		DI	Regulations				LTT	RD&D	Other
			FIT	FiP	Auct.	Tax cr.	Grant	Loan	ITC	Guar	C tax	ETS	GCE		RPS	NM	TS	GP			
Schallenberg-Rodriguez and Haas [87]	ES	RES	±	±																	
Buckman [160] (*)	GB, US	RES													●						
Wiser et al. [105]	US	RES													(+)						
Lauber [12]	GB, DE, US	RES	+												(+)						
Del Río and Linares [139] (*)	IE, GB, FR, PT, CN, IN, CA (Quebec), BR, AR, UY, PE, ZA, MA)	RES			(+)																
Aquila et al. [173]	BR	RES	(+)		+												●				
		Wind	+		+												●				
		PV	(+)		(+)												●				
		Bio	●		●												●				
		SHP	●		●												●				
Mora et al. [90] (*)	BR, CN, DK, FR, DE, IE, IT, NL, PT, ZA, ES, GB, US-CA	RES (PV, Wind, Bio			(+)																
Geddes et al. [80]	DE, UK, AU	RES							(+)	(+)				(+)					(+)		
Haas et al. [46]	EU, 27 countries	RES (PV, Wind)	+		(+)	(+)		(+)				(+)			(+)						
Winkler et al. [95]	BR, FR, IT, NL, ZA	RES			±																
		Wind			±																
		PV			±																
		Biomass			±																

FIT = Feed-in-tariff, FiP = Feed-in-premium, Auct. = Auction/PPA, Tax cr. = Production tax credit/relief, Grant = Grants, Loan = Subsidized investment loan/funds, ITC = Investment tax credit, Guar = Guarantees, ETS = Emission trading scheme, GCE = Green certificates, DI = Direct investment, RPS = Quotas/RE portfolio standards, NM = Net metering, TS = Technical Standards, GP = Grid Preference, LTT = Long-term targets/commitments, RD&D = Research Development and Demonstration, RES = Renewable Energy Systems in general, Wind = Onshore and Offshore Wind, PV = Photovoltaics, ST = Solar Thermal Energy, Bio = Biomass and Waste-to-Energy, Geo = Geothermal Energy, SHP = Small Hydro Power, M/LHP = Medium and Large Hydro Power, Marine = Marine Energy, Other = Other

+ = positive, - = negative, ± = positive and negative, ● = considered in paper, no instrument effect specified, [blank] = not considered in paper.

(*) = Paper does not (or sparsely) evaluate policy effects, but discusses design elements, circumstantial effects or others in detail.

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Paper 3

A dynamic analysis of financing conditions for renewable energy technologies

Citation: Egli, F., Steffen, B., & Schmidt, T. S. (2018). A dynamic analysis of financing conditions for renewable energy technologies. *Nature Energy*, *3*(12), 1084–1092. https://doi.org/10.1038/s41560-018-0277-y

Contributions: T.S.S., B.S. and F.E. developed the research idea. F.E., B.S. and T.S.S. conducted the investor interviews, collected, analysed and interpreted the data, and wrote the manuscript.

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Abstract

Renewable energy technologies often face high upfront costs, making financing conditions highly relevant. Thus far, the dynamics of financing conditions are poorly understood. Here, we provide empirical data covering 133 representative utility-scale photovoltaic (PV) and onshore wind projects in Germany over the last 18 years. These data reveal that financing conditions have strongly improved. As drivers, we identify macroeconomic conditions (general interest rate) and experience effects within the renewable energy finance industry. For the latter, we estimate experience rates. These two effects contribute 5% (PV) and 24% (wind) to the observed reductions in levelised costs of electricity (LCOEs). Our results imply that extant studies may overestimate technological learning and that increases in the general interest rate may increase renewable energies' LCOEs, casting doubt on the efficacy of plans to phase out policy support.

Energy Politics Group

A dynamic analysis of financing conditions for renewable energy technologies

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Published in *Nature Energy*
Please cite article as: Egli, F., Steffen, B., & Schmidt, T. S. (2018). A dynamic analysis of financing conditions for renewable energy technologies. Nature Energy, 3(12), 1084–1092.

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Renewable energy technologies often face high upfront costs, making financing conditions highly relevant. Thus far, the dynamics of financing conditions are poorly understood. Here, we provide empirical data covering 133 representative utility-scale photovoltaic (PV) and onshore wind projects in Germany over the last 18 years. These data reveal that financing conditions have strongly improved. As drivers, we identify macroeconomic conditions (general interest rate) and experience effects within the renewable energy finance industry. For the latter, we estimate experience rates. These two effects contribute 5% (PV) and 24% (wind) to the observed reductions in levelised costs of electricity (LCOEs). Our results imply that extant studies may overestimate technological learning and that increases in the general interest rate may increase renewable energies' LCOEs, casting doubt on the efficacy of plans to phase out policy support.

Keywords: energy finance, WACC, cost of capital, financial learning

The Energy Politics Group (EPG) within the Department of Humanities, Social, and Political Sciences of ETH Zurich investigates questions related to the governance of technological change in the energy sector.

Keeping climate change within safe limits and achieving the goals of the Paris Agreement require fast and ample redirection of financial flows towards low-carbon technologies[1–3]. As approximately two-thirds of global greenhouse gas emissions stem from the energy sector[4], the rapid deployment of low-carbon energy technologies, such as renewable energy technologies (RETs), is crucial for emissions reductions[5]. Solar photovoltaics (PVs) and wind will likely play central roles in this transition[6]. Importantly, as RETs are more capital intensive than fossil fuel technologies large portions of their life-cycle cost are incurred upfront and need to be financed[7,8]. Extant literature has established the adverse effect of high costs of capital on the levelised costs of electricity (LCOEs) for RETs[9], CO_2 abatement cost[7,10] and RET deployment in integrated assessment models[11]. Consequently, high costs of capital are considered major obstacles to RET deployment[12,13]. By the same logic, low costs of capital can contribute to the observed cost reductions for solar PV and wind energy[14–16]. Financial markets thus have a constraining or enabling role in the low-carbon energy transition[17–20].

While individual investors know their cost of capital, typically this information remains unavailable to researchers[21,22], especially concerning developments over time. This paper addresses this gap, by analysing the German solar PV and onshore wind power financing market, which has a particularly long investment history[23]. We exploit the fact that utility-scale renewable energy investments in Germany are almost exclusively realised in project finance structures[24] (see Supplementary Note 1 for a description), in which the costs of capital reveal unbiased information about the underlying investment projects and technologies[25]. We proceed in four steps. First, using newly complied project data, we depict the cost of capital and its components and analyse the changes over 18 years. Second, we use qualitative insights from in-depth interviews with 41 investment professionals to identify the drivers of the observed changes in financing conditions. Third, we quantify an experience effect within the renewable energy finance industry, leading to lower costs of capital. Fourth, we quantify the effect of the observed changes in costs of capital on LCOEs. The methods are structured along the same four steps. We find that the cost of capital (CoC) declined by 69% for solar PV and by 58% for wind onshore projects between the early period of the RET finance industry (2000–

2005) and 2017. For both technologies, the cost of debt decreased more than the cost of equity. Focusing on the cost of debt, we identify and estimate a financing experience curve. For each doubling of cumulative investment, the debt margins (see Supplementary Table 1 for definitions of financial terms) decreased by 11% for both technologies. During the same time, we observe a decline in the general interest rate resulting in lower costs of capital that had a substantial effect on the economic attractiveness of RETs. Finally, we estimate that 41% of total solar PV LCOE reductions and 40% of wind onshore LCOE reductions between 2000–2005 and 2017 were due to lower financing costs. These result from three effects: lower capital expenditures (CAPEX) to be financed (strongest effect for solar PV), lower general interest rate (strongest effect for wind onshore), and financing experience. We conclude with implications for researchers and policymakers.

Changes in financing conditions

In the first step, we analyse the temporal dynamics of the CoC and its components (see Methods). We compile data on the financing conditions of 133 representative utility-scale renewable energy projects, undertaken between 2000 and 2017, to establish the temporal dynamics of costs of capital for solar PV and wind onshore. The project data is provided by leading renewable energy investors, covering lead arrangers responsible for 85% of the solar PV and 80% of the wind onshore investment sums between 2000 and 2017 (see Supplementary Figure 1). Figure 1 displays the cost of debt, the cost of equity and the CoC for all projects in our dataset. Both solar PV and wind onshore projects experienced substantial decreases in costs of capital. While some variance in CoC is normal due to slightly different project conditions, the data shows a clear decrease in the lower bound for cost of debt and cost of equity over time. The lower bound of cost of debt dropped from around 5% to less than 0.5% for both technologies. Lower bound equity returns fell from around 10% to below 4%.

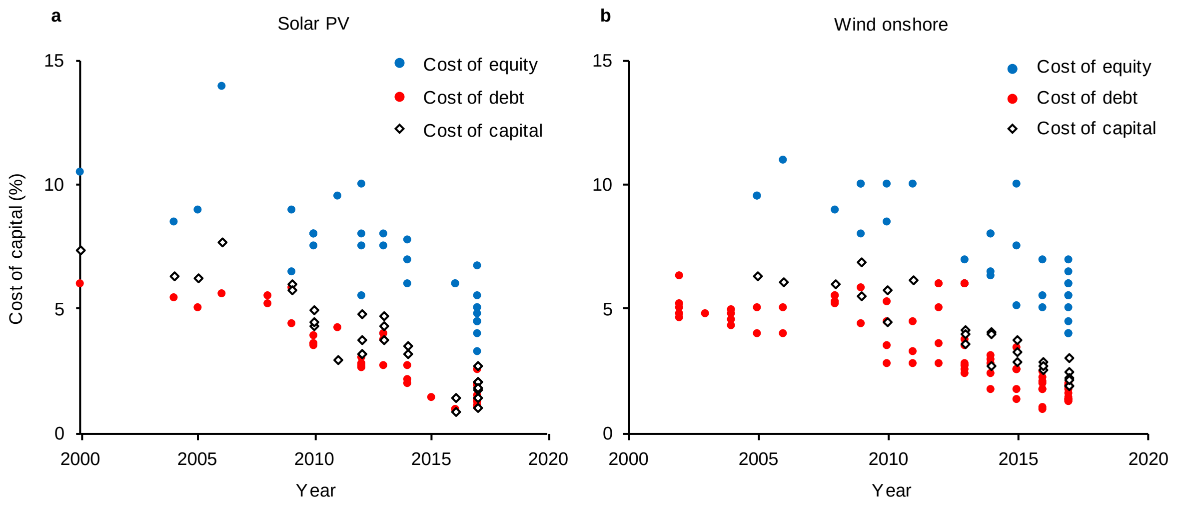

Figure 1: Costs of capital over time. Cost of debt, cost of equity and average (by project) CoC in Germany for (**a**) 43 solar PV and (**b**) 78 wind onshore projects between 2000 and 2017 (N = 121). We show CoC numbers only for projects where cost of debt and cost of equity, as well as capital structure (leverage), are known (29 solar PV and 26 wind onshore projects).

Figure 2 draws on the same data as Figure 1 to calculate the average across projects and compares the early period of the RET finance industry (2000–2005) to 2017. It first shows that the cost of debt decreased more than the cost of equity in relative terms and that decreases in both components were more pronounced for solar PV than for wind onshore. However, the project CoC also depends on the leverage and the corporate tax rate. Leverage denotes the share of debt of the total investment sum (see Methods). Because equity bears the first project losses, a higher leverage is an indication for lower project risk. For both technologies, the leverage increased, reaching over 80% debt financing in 2017 (see Supplementary Figure 2). During this period, the German corporate tax rate decreased from 41% to 30%, resulting in relatively higher costs of debt as interest rate payments are deductible from taxable revenues.

Figure 2c and 2d summarize the resulting after-tax CoC. The CoC in 2017 were in the range of 1.6% (solar PV) to 1.9% (wind onshore), corresponding to a low-risk corporate bond of a financial service firm (BB+ to BBB)[26]. Stated differently, CoC declined by over two-thirds (3.5% points) for solar PV projects and more than half (2.6% points) for wind onshore projects. While the cost of capital for solar PV projects in 2000–2005 was higher than for wind onshore projects, the former had a lower cost of capital than the latter in 2017. Similar trends were observed for additional financial indicators, such as loan tenors and debt service coverage ratios (see Supplementary Figure 2). Over our study period, the duration of the feed-in tariff stayed constant at 20 years. Banks offering longer loan tenors is therefore an indication of higher confidence in the project. The debt service coverage ratio (DSCR) is a measure of project cash flows available to pay debt obligations, namely the principal repayment and interest rate payments. Lower DSCRs can thus be interpreted as an additional indication for lower project risk.

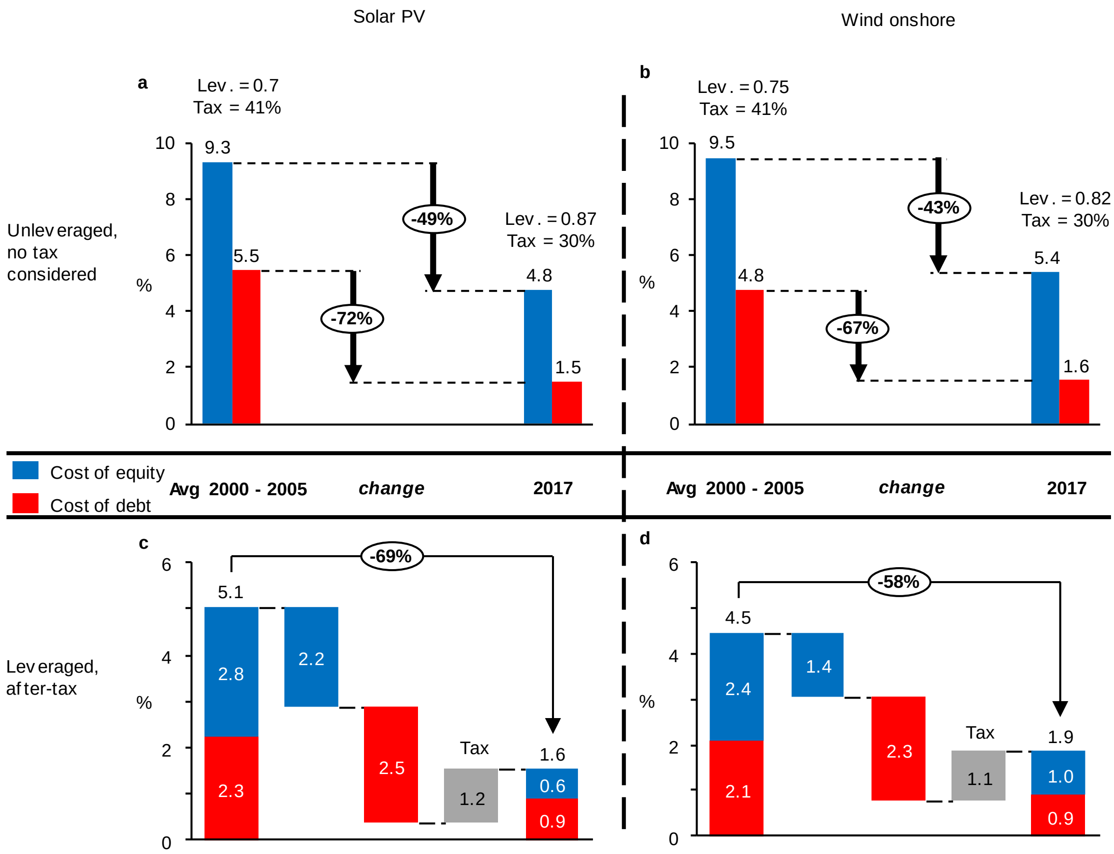

Figure 2: Components and dynamics of cost of capital. First row: changes in unleveraged (pre-tax) cost of debt and cost of equity **(a)** for solar PV and **(b)** wind onshore projects. Second row: changes in leveraged (after-tax) CoC **(c)** for solar PV and **(d)** wind onshore projects. The positive tax effect was due to a decrease in the corporate tax rate that led to a smaller cost reduction from tax deductible debt interest payments.

Drivers of change

In the second step, we use qualitative interviews with investment professionals (N = 41, see Supplementary Table 3) to inductively reveal and understand the underlying drivers of the observed changes in financing conditions[27]. Averaging more than ten years of renewable energy investment experience, the interviewees demonstrate an in-depth understanding of the market dynamics over time. From these interviews, we distil drivers of cost of capital reductions on three nested levels: the macroeconomic environment (economy), the renewable energy sector, and the renewable energy *finance* industry (see Methods). The latter two are related to experience gained through deployment and financing of RET. Figure 3 illustrates the main drivers on the three identified levels.

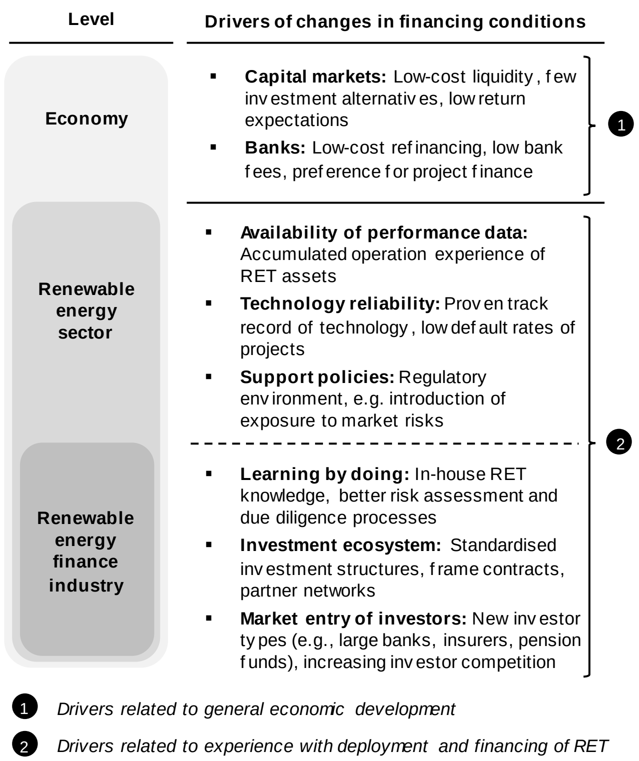

Figure 3: Drivers of changes in financing conditions in a nested hierarchy (see Methods). The general economic environment led to more favourable financing conditions (for all sectors) over the period of our study. All drivers in the renewable energy sector and the renewable energy finance industry contributed to more favourable financing conditions (in the renewable energy sector) over the period of our study, with the exception of changes to support policies, which potentially introduce new uncertainties into RET deployment.

On the economy level, expansive monetary policies in the aftermath of the 2008–2009 financial crisis resulted in low refinancing costs for banks, which decreased the cost of capital of the economy[28]. The large supply of capital increased the pressure on bank fees and eventually lowered them, too. At the same time, extensive bank lending tended to lead to overconfident credit issuance, thereby increasing default rates[29,30]. The extensive lending made the evaluation of companies' credit eligibility more difficult and thereby increased the investment attractiveness of projects with predictable cash flows, such as RET assets in project finance structures.

On the renewable energy sector level, technology deployment had a favourable impact on financing conditions. As more renewable energy projects were undertaken, technologies became more mature, that is, more reliable. In parallel, the availability of data on technology performance made an assessment of this increasing reliability possible, while financial data showed low default rates. Together with a higher confidence in partners for construction and operation of RET assets, as these companies had increasingly established track records, these developments provided impetus for investment professionals to convince their boards to invest in renewable energy assets. According to our qualitative results, the deployment effect was more pronounced for solar PV than for wind onshore projects because of wind turbines' larger operational risk due to their design complexity[31] and moving parts. Additionally, wind resource availability is more difficult to predict than solar irradiation. Partly as a result of these factors, the CoC decreased faster for solar PV projects than for wind onshore projects. Finally, stable and reliable RET support policies were a prerequisite for RET investment in Germany in the past[23]. However, gradually, some RET projects are being partly exposed to market prices[32,33], which is reflected by few shorter loan tenors and higher DSCRs (see Supplementary Figure 2).

On the level of the renewable energy *finance* industry, investors benefited from growing RET markets and subsequent learning-by-doing (e.g., better risk assessment)[34]. Larger markets allowed banks to form in-house project finance teams specialised in RETs. The knowledge and data that these teams accumulated allowed for a more accurate technology assessment.

Consequently, project risks declined. For example, as the market had accumulated experience on historical wind speeds, investors shifted from calculating project returns on wind resource estimations with 90% certainty (90th percentile of the distribution, p90) to trusting the median (p50). While the observed increases in loan tenors and decreases in DSCRs (see Supplementary Figure 2) confirm lower project risk, we see two divergent trends in project leverage. On the one hand, investors advanced to higher leverages to increase returns on equity; on the other hand, some investors started to accept lower leverages to place their equity in a market environment with few renewable energy investment opportunities on offer.

Moreover, the investor ecosystem matured and competition increased. In a maturing investment market, institutional investors (e.g., insurers and pension funds) started to perceive renewable energy project finance as an attractive asset class. Institutional investors usually demand lower returns and larger project sizes than smaller early-stage investors[35]. The capital inflow from the new group of institutional investors hence created an incentive to build larger projects and increased competition for projects, which generally compressed debt margins further. While lower margins lead to lower LCOEs and are thus potentially conducive to RET deployment, some investors fear that the increasing capital inflow could create an asset bubble with financing conditions that would no longer reflect project risks. Lastly, the use of standardised deal structures facilitated the investment process and contributed to more efficient financing markets with lower margins.

Financing experience rates

The third step of our analysis focuses on the effects that are related to experience with deployment and financing of RETs (see Figure 3). The innovation literature has identified a roughly constant percentage unit cost decline – the experience or learning rate – with each doubling of cumulative production (Wright's law, see Methods)[36]. This experience effect is a well-known characteristic of RET investment cost[14–16,37,38]. Our results from the second step demonstrate that experience matters for the renewable energy finance industry. We hence propose a financial experience effect analogous to Wright's law[39] and estimate a corresponding experience rate.

To identify the experience rate, we focus on debt, because this is where most cost reductions have occurred (compare Figure 2). We analyse three debt indicators that reflect investment safety margins, namely, the debt margin, DSCR and loan tenors. For riskier projects, investors demand higher debt margins as compensation, an increase in the DSCR to create a buffer in case of cash flow complications, and a decrease in the loan tenor to reduce the risk exposure to a shorter period. More experienced investors should be able to judge investment projects more accurately, thereby reducing the required safety margins and generating an empirically observable experience effect. Figure 4 shows the experience rates for the three variables. We find an experience rate of 11% on the debt margins of both technologies. We also detect experience rates of 13% for the DSCR of solar PV projects and of 17% for the DSCR of wind onshore projects (see Methods). Regarding the loan tenors, we find an experience rate of -3%, that is, increasing loan tenors with increasing experience. However, this finding is insignificant for wind onshore projects. In sum, the third step of our analysis establishes the statistical significance of the experience effect in renewable energy financing, as found qualitatively in the second step. Increased RET deployment contributes to better financing conditions.

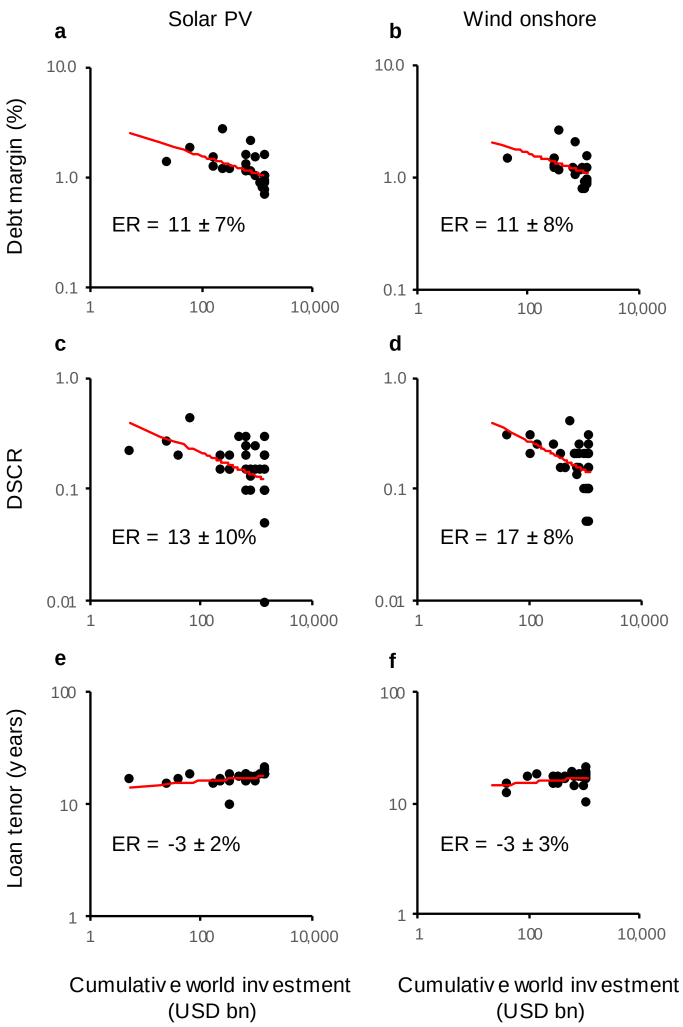

Figure 4: Experience rates (ER) for risk metrics including the 95% confidence interval. **a,** Debt margin ER for solar PV projects (N = 27) and (**b**) for wind onshore projects (N = 22). **c**, Debt service coverage ratio (DSCR) ER for solar PV projects (N = 35) and (**d**) for wind onshore projects (N = 36). **e**, Loan tenor ER for solar PV projects (N = 36) and (**f**) for wind onshore projects (N = 34). All axes are in logs, and fits are linear. All linear fits are significant at the 5% level or below, except for the wind onshore loan tenors (f). Data from German projects between 2000 and 2017. Between 2000 and 2017, global cumulated solar PV investment doubled eight times, and wind onshore investment just short of six times. Results are robust to including investor fixed effects (e.g., controlling for different sizes of investors), choosing Europe as the relevant scope for experience (i.e. using European instead of global investment data) and using alternative data to measure investment (see Supplementary Tables 5-7).

In the following, we compare the experience effect with the exogenous effect (economy level) from changes in general interest rates. The cost of debt of a RET project can be decomposed into two elements covering the baseline country risk and project specific risk[40]. Figure 5 shows the yields of a 10-year German government bond (the best proxy for baseline country risk) and the estimated debt margins (the best proxy for project specific risk). While the bond yields are driven by monetary policy and exogenous to renewable energy deployment, the debt margins reflect dynamics related to experience with deployment and financing of RET.

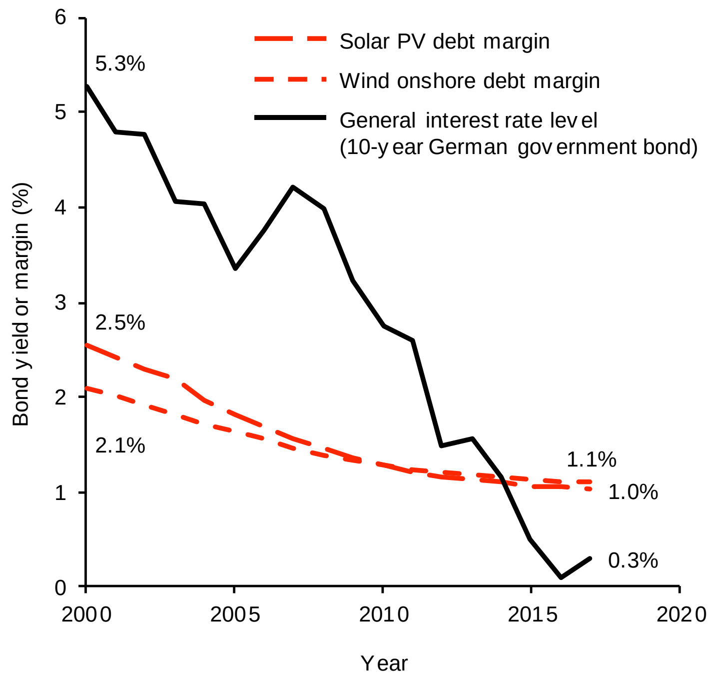

Figure 5: Changes in the baseline country risk versus project risk. Debt margins are predicted values using the estimated experience rate from Figure 4 and global investment data from 2000 to 2017 (see Methods). A data validity check regarding the decomposition of the cost of debt into debt margin and government bond yield is provided in Supplementary Figure 4.

Three observations can be made in Figure 5. First, the change in debt margins seems small compared with government bond yields but is economically substantial. While government bond yields decreased by 5% points, debt margins have declined by 1.5% points for solar PV projects and 1% point for wind onshore projects between 2000 and 2017. For comparison, this decrease corresponds to a change in the corporate ratings of a financial service firm from B+ to AAA for solar PV or from BBB to AAA for wind onshore[26]. Second, Figure 5 reveals different dynamics between the two technologies. Due to larger increases in cumulative investment for solar PV, its debt margin decreased more than it was the case for wind onshore projects. As a relatively novel technology, solar PV projects were perceived riskier and thus charged with a higher debt margin in 2000. In 2017, investors no longer make a difference and charge almost identical margins. This catch-up of solar PV confirms the pattern shown in Figure 2 and the qualitative findings from the previous section. Third, debt margins are higher than the baseline country risk rate in 2017, largely as a result of exceptionally low government bond yields due to the expansive monetary policy after the financial crisis. Considering the observed trend towards higher leverages and the concurrently increasing importance of the cost of debt, this finding points out that changes in the general interest rate level potentially have a large impact on the cost of capital for RETs.

Impact on LCOE

In the fourth and final step, we calculate the LCOE in the early period of the RET finance industry (2000–2005) and in 2017 (see Methods).

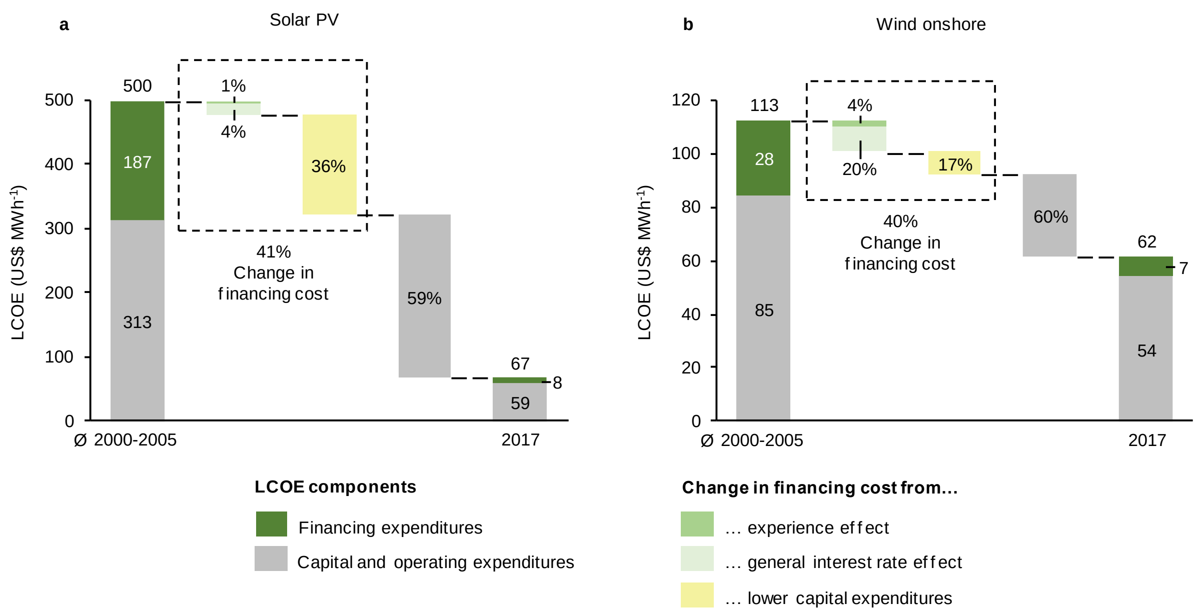

Figure 6: Historical impact of changes in financing costs on levelised cost of electricity (LCOE). Shown for (**a**) solar PV and (**b**) wind onshore. Percentages indicate the contributions of the respective parts to the change in LCOE. We parametrise the LCOE model using data for Germany (see Supplementary Table 4). Sensitivities are provided in Supplementary Figure 5. Numbers do not always add up due to rounding.

Figure 6 shows that the LCOE declined for both technologies, bringing both technologies into the generation cost ranges for fossil fuel-fired power plants, estimated to be between US$50 and US$170 for G20 countries in 2017[41]. Around 60% of this decline is due to lower technology cost (CAPEX) with the remaining 40% due to lower financing cost. Three effects contribute to the change in financing costs. First, the initial investment to be financed (CAPEX) decreased, which lowers the financing cost. Second, the general interest rate decreased. Third, an experience effect led to the compression of financing margins. The three effects differ in importance between the two studied technologies. The large reduction in Solar PV CAPEX during the period of our study (see Supplementary Table 4) led to lower financing costs, which contributed to roughly one third (36%) of LCOE reductions. Conversely, onshore wind CAPEX stayed relatively constant (see Supplementary Table 4), increasing the relative importance of the general interest rate effect, which contributed to one fifth (20%) of LCOE reductions. Thus, the channels through which financing costs contribute to lowering LCOEs vary according to the relative reductions in CAPEX. As solar PV and wind onshore are becoming mature technologies and future CAPEX reductions become less likely, the relative importance of the general interest rate and experience effects will increase.

Discussion

This paper compiles a project level dataset for financing conditions and makes three contributions. First, it identifies the drivers of the changes in financing conditions. Second, it estimates an experience effect for financing conditions and compares it with the changes in the general interest rate. Third, it demonstrates the effect of the changes in financing conditions on the LCOE.

For researchers, our results suggest that the dynamics of financing conditions should receive more attention in models that include investments in low-carbon technologies. In failing to account for these dynamics, researchers could overestimate the technology learning effect by attributing the full LCOE change to reductions in capital and operating expenditures. Accounting for different channels of LCOE reductions via financing costs may be particularly important – especially as the increasing use of auctions makes data on generation costs readily available, increasing the use of LCOE learning curves[41]. To include sensitivity analyses regarding the dynamics of financing conditions in models, further research should help improve the understanding of the processes that affect renewable energy financing conditions. While we have separated three effects contributing to financing costs' LCOE effect, their dynamics are yet to be fully understood, opening up avenues for future research. For example, it is not evident whether deployment and the associated reductions in investment costs would have been as large as observed without reductions in the CoC. The accumulation of experience in the finance industry, the excess availability of capital and the reductions in investment costs all depend on each other and together constitute the impact of financing costs on the LCOE. Future research also should investigate to what extent this paper's conclusions are applicable to other regions and other technologies.

For policymakers, our findings stress the importance of policies that are conducive to favourable financing conditions for RETs. First, our results suggest an important co-benefit of deployment policies: the acceleration of technological change by allowing the finance industry to experiment and learn. RET investments are long-term, and the finance industry typically struggles to assess long-term risks of new technologies without track record[34,42]. For instance, green state investment banks can be an instrument to accelerate learning in the finance industry, helping investors assess projects and build confidence in new technologies[43]. Second, our results indicate that a large RET financing market and a high degree of competition between investors were crucial in creating more favourable financing conditions for RETs. Therefore, policies should try to crowd-in a broad spectrum of investors. Third, our findings point out that policymakers should be vigilant in responding to changes in monetary policies that have an impact on RET costs. As RET generation costs approach grid parity, policymakers in some countries consider phasing out fixed remuneration schemes for RETs. While some have argued that achieving high RET shares requires de-risking policies in any case[44], our results stress the particular importance of policy intervention (e.g., RET support or carbon pricing) given the likelihood of an imminent increase in interest rates. Ending policies might be premature and put climate change targets at risk. Policymakers also could evaluate new approaches, such as green monetary policies, to ensure attractive financing conditions for RETs and other low-carbon technologies in the future[45].

Methods

Case selection

The case selection includes three dimensions: technology, country and project type. First, we focus on solar PV and wind onshore technologies, the most deployed non-hydro RETs. In 2016, solar PV and wind onshore technologies accounted for a global capacity of 291 GW and 452 GW, respectively (e.g., compared with 14 GW for wind offshore generation)[46]. Second, we focus on Germany, one of the earliest markets to adopt these technologies. Germany added the most solar PV capacity in 13 of the 17 years analysed, and the most wind onshore capacity in eight of the 17 years analysed[46]. Our sample period begins in 2000, when Germany enacted its landmark legislation on renewable energy sources (EEG), with a feed-in tariff that triggered large-scale renewable energy investments[23]. The feed-in tariff was never changed retroactively. The German electricity market has been liberalised since 1998[23], and the vast majority of investment in RET was private[47]. Third, we restrict the analysis to project finance structures, exploiting the fact that 96% of large solar PV projects and 88% of large wind onshore projects in Germany between 2000 and 2015 were undertaken using project finance[24].

Data collection

We contacted leading investors directly to assemble two sets of data: quantitative data on the financing conditions of reference projects, and qualitative data on the drivers of changes in financing conditions. The former is used for steps one, three and four of the paper, and the latter is used for step two. All investor interviews were conducted between September 2017 and January 2018, following the Chatham House Rule, which states that 'participants are free to use the information received, but neither the identity nor the affiliation of the speaker(s) […] may be revealed'[48]. The interviews were conducted in person or over the phone by one to three researchers who took individual notes. All interviews were recorded and transcribed verbatim.

We use theoretical sampling to include the most revelatory interviewees and balance our sample to represent various perspectives from the finance industry[27,49]. The sampling took place in three stages. First, we searched for publicly available addresses of senior investment professionals working at large debt and equity investment firms, using the Bloomberg New Energy Finance (BNEF) database[50]. Second, we used the contact network of a private renewable energy finance industry partner in the INNOPATHS research consortium, Allianz Climate Solutions (ACS), to reach out to relevant market actors. Third, we employed snowball sampling by asking key contacts from our network to refer us to relevant actors and teams, then continued to ask for references upon each contact with an investment professional. The resulting sample is well-balanced among different kinds of financial actors and includes 17 debt providers (13 commercial banks and four investment banks), 16 equity providers, seven public actors (four public utilities and three public investment banks), and one former researcher (see Supplementary Table 3 for the full interviewee sample). The sampled financial actors were lead arrangers in 81% of solar PV capacity additions and 85% of the solar PV investment sum, and in 49% of onshore wind capacity additions and 80% of the onshore wind investment sum, between 2000 and 2017 (see Supplementary Figure 1). Thus, our sample covers the relevant actors in a balanced manner and is relevant in size to elicit financing conditions that are representative of the German investment market. Reflecting the international nature of the renewable energy finance industry, the investors in our sample are based in Germany, Switzerland, the UK, the Netherlands, France, Italy, Luxemburg and Norway (see Supplementary Table 3).

Quantitative data

To ensure comparable data on project financing conditions, we defined a reference project with an investment sum of €20 million, using standard technology from established manufacturers (poly-crystalline modules without a tracker for solar PV projects and 1.5–2 MW turbines on a standard foundation for wind onshore projects). While the relatively small standard deviation of the data (see Supplementary Table 2) indicates a good comparability of projects across investors, we control for investor differences (e.g., investor size) by including investor fixed effects in the estimations of experience rates (see below).

We asked the investment professionals to provide information on the all-in cost of capital, cost of debt, cost of equity, debt margin, DSCR, leverage (i.e., project capital structure) and loan duration (tenor) for any such reference project that they had financed (which is the case for 37 interviewees) or had advised on (which is the case for four interviewees; see Supplementary Table 3) between 2000 and 2017 (see Figure 1 and Supplementary Figure 2). For cost of capital components (cost of debt, cost of equity and leverage), the interviewees were free to indicate ranges instead of absolute values, in which case, we take the average by project. Wherever possible, the debt providers indicate not only the all-in cost of debt, but also the debt margins. For projects with available information on debt margins, we calculate the all-in cost of debt as the sum of the baseline rate (10-year government bond[51]) and the debt margin. This approach yields all-in cost of debt data comparable to where debt providers revealed all-in costs of debt (see Supplementary Figure 4). Additionally, we screen publicly available onshore wind park investment prospectuses – mainly from civic-owned assets (German *Bürgerwindparks*) – between 2000 and 2017 for the data on the cost of debt. We do not consider this source for the cost of equity data because investment prospectuses often offer overly optimistic equity returns *ex-ante*. On the other hand, the cost of debt figures reflect the rates offered by banks. The resulting dataset consists of 48 solar PV and 85 wind onshore projects. The number of observations, means, standard deviations, and minimums and maximums for all variables are described in Supplementary Table 2.

To estimate experience rates, we use investment data from the United Nations Environment Programme (UNEP)[52], which is available from 2004 onward. For the years prior to 2004, we take global investment costs per MW for solar PV and wind onshore projects[50] and multiply these figures with global capacity from the International Renewable Energy Agency (IRENA)[46]. For 2000 and 2001, we used the solar PV investment costs from 2002 because ref. 46 provides no data. For 2017, we extrapolate the changes from the previous year.

Qualitative data

To develop the drivers of changes in financing conditions, we apply an interview case study design with two stages of data collection[53]. First, open exploratory interviews (N = 8) were conducted to gain early insights on the dynamics and drivers of changes in financing conditions and to define the structure for the second phase of the interviews. Second, we conducted 33 semi-structured interviews with employees from debt and equity investment firms who had significant experience in the renewable energy finance industry (23 of these interviewees are the same individuals who provided the quantitative data mentioned above). Note that we contacted three investment professionals from the exploratory interviews again for the semi-structured interviews and the collection of project financing conditions data.

If more than one researcher conducted an interview (N = 15), one of them summarised it using the recording, transcript and notes. If only one researcher conducted the interview (N = 26), the resulting summary was cross-checked by another researcher. This procedure ensures accurate and consistent recording, expands the scope of insights and enhances confidence in the findings[53]. Following Eisenhardt's approach[53], we continued holding interviews until no additional insights were observed.

Changes in financing conditions

In the first step of the paper, we calculate the project cost of capital (CoC) before and after taxes because the German corporate tax rate was cut four times, from an initial 52% in 2000 to 30% in 2008, and remained at that level until 2017[54] (see Supplementary Figure 3). Equations (1) and (2) define the pre- and after-tax CoC.

$$\text{Pre-tax CoC} = K_E \frac{E}{V} + K_D \frac{D}{V} \tag{1}$$

$$\text{After-tax CoC} = K_E \frac{E}{V} + K_D \frac{D}{V}(1 - T) \tag{2}$$

In these equations, E and D denote equity and debt investment, respectively; V signifies the total investment sum; K_E and K_D refer to cost of equity and cost of debt, respectively; and T represents the corporate tax rate. The leverage L is equal to D/V. To analyse the changes over time, we use the average during the 2000–2005 period as the starting point due to limited data availability in the early years. Because costs of capital decreased already between 2000 and 2005, this approach yields a conservative estimate for the changes over time.

Taking the derivatives of Equation (2) yields Equations (3-6), below. Equations (3) and (4) show that the changes in the cost of equity and debt affect the cost of capital, depending on leverage and corporate tax rate. Equation (5) shows that the effect of increasing leverage depends on the difference between K_D and K_E. More precisely, if $(1-T)K_D < K_E$ holds, the cost of capital decreases with increasing project leverage. Typically, this condition holds in reality (see characteristics of project finance above). Equation (6) illustrates that a change in the tax rate affects costs of capital in the opposite direction, i.e., a decrease in the tax rate increases costs of capital.

$$\frac{\partial CoC}{\partial K_E} = (1-L) \tag{3}$$

$$\frac{\partial CoC}{\partial K_D} = (1-T)L \tag{4}$$

$$\frac{\partial CoC}{\partial L} = (1-T)K_D - K_E \tag{5}$$

$$\frac{\partial CoC}{\partial T} = -LK_D \tag{6}$$

Figures 2c and 2d represent this fact with a grey upward bar for tax changes, indicating the higher cost of capital due to the lower corporate tax rate.

Drivers of change

In the second step, we use qualitative data to establish the drivers behind the changes in financing conditions. The interviews were semi-structured in the sense that the interviewees were free to name and explain the main drivers that led to the changes in financing conditions, but the conversations followed a pre-determined set of topics. At the end of each interview, we asked the interviewee whether crucial points were missing. This feedback was included iteratively in the first few interviews. Key statements were summarised by two researchers after each interview. Once the interview summaries were completed (see data collection above), we loosely followed the 'grounded theory' approach[55] by comparing incident (i.e., statement) to incident to iteratively create common patterns and drivers. We constantly compared new incidents with emerging drivers (recursive cycling among different investor interviewees)[27]. Two researchers conducted this 'constant comparison', verifying drivers and ensuring their accuracy[56]. As a result, we identified eight drivers, which we categorised in a nested hierarchy of three levels: economy, renewable energy sector and renewable energy finance industry.

Financing experience rates

In the third step, we apply a one-factor experience curve, following Wright's law[39], and adapt it to financial indicators. Applying a one-factor experience curve may lead to estimates that are biased upwards due to an omitted variable bias[57]. The most commonly cited omitted factor is research and development (R&D) spending[38,58]. However, service industries, such as the finance industry, typically do not use R&D departments, or even the term R&D. Instead, innovation activities are organized in project-based teams[59]. Perhaps as a consequence, some empirical evidence even points to a negative effect of R&D spending on service innovation[60]. Finally, the evidence of our interviews points to factors such as track records, improved processes or market competition as drivers of the experience effect. Quantifying these factors individually is impossible, which is why we choose to use a one-factor experience curve and discuss the components qualitatively in step two. For each of the financial indicators (i.e., debt margin, DSCR and loan tenor), we define experience curves as follows:

$$DebtMargin(I_t) = DebtMargin(I_0)\left(\frac{I_t}{I_0}\right)^{-b_1} \quad (7)$$

$$DSCR(I_t) = DSCR(I_0)\left(\frac{I_t}{I_0}\right)^{-b_2} \quad (8)$$

$$Tenor(I_t) = Tenor(I_0)\left(\frac{I_t}{I_0}\right)^{-b_3} \quad (9)$$

In Equation (7), *DebtMargin* denotes the debt margin in percentage points. In Equation (8), *DSCR* signifies the transformed debt service coverage ratio. We transform the elicited DSCR values by subtracting 1 because the DSCR has a natural lower bound of 1. As we are taking the log in the next stage, we transform one value in our sample from 0 to 0.01. In Equation (9), *Tenor* represents loan tenor duration in years. In all three equations, *I* refers to the cumulative world investment volume in billions of US dollars, and $b_{1–3}$ signifies the experience parameter for each variable. In each Equation (7–9), I_0 denotes the first investment, and I_t represents cumulative investment at time *t.*

We define an individual experience rate, $ER = 1 - 2^{-b}$, for each variable of interest and quantify it by estimating Equations (7–9) separately for both technologies *i*, using an ordinary least squares (OLS) regression according to Equation (10):

$$\ln(DV_{it}) = \beta_{0i} + \beta_{1i}\ln(I_{it}) + \varepsilon_i\,, \quad (10)$$

In which *t* denotes the year, *DV* denotes the dependent variable (see Equations 7–9), and, again, *I* signifies cumulative world investment in billions of US dollars.

As mentioned previously, a potential caveat concerning the data is the heterogeneity of investors. Thus, we apply investor fixed effects in a robustness check, which does not change the results (see Supplementary Tables 5 and 6). The choice of the independent variable in the specification of the experience rate also is subject to some debate in extant literature. Depending on the technology and application, the relevant geographical scope to accumulate experience changes[61], which affects the empirical identification of experience rates[58]. While the evidence indicates global experience effects for RETs because innovation benefits cannot be kept locally[34], this argument should hold even more for the finance industry – especially as large investors usually are active internationally. Our choice of cumulative global investment is driven by exploratory investor interviews, which point out that the financing of large project finance deals is international and increasingly global, so global investment figures appear to be the most relevant. However, because our investor sample is Europe-based (see Supplementary Table 3), we test for a European specification of the experience effect by using cumulative European investment. We do so by using capacity data for Europe from IRENA[46] and investment cost data for Germany from BNEF[50] (three-year moving average). The results remain very similar for solar PV, but estimates for the wind onshore experience rate become larger (see columns 3 and 4 in Supplementary Tables 5 and 6). Finally, we conduct a robustness check with alternative investment data sources, using global data on investment cost per MW[50] (three-year moving average) and IRENA data on global capacity additions[46]. The results do not change (see columns 5 and 6 in Supplementary Tables 5 and 6). We always use robust standard errors to allow for heteroscedastic residuals (e.g., decreasing variance of the error term with decreasing debt margins because the market is becoming more competitive). Along most specifications, the results remain very similar. In cases when they change, we report a conservative experience effect by using global cumulative investment (i.e., typically equal or close to the lowest value across specifications). We report the range of the estimated experience rates across all specifications in Supplementary Table 7.

Impact on LCOE

In the fourth step, we calibrate an LCOE model according to Equation (11) to quantify the effect of the observed changes in financing costs on lifetime RET generation costs. We calculate the LCOE for both technologies *i* (solar PV and wind onshore) and the two points in time, *t (t=1 in 2000-2005; t=2 in 2017*), as displayed in Figure 6.

$$LCOE_{it} = \frac{C_{it} + \sum_{\tau=1}^{\tau=20} \frac{C_{it\tau}}{(1+CoC_{it})^{\tau}}}{\sum_{\tau=1}^{\tau=20} \frac{FLH_{it\tau}}{(1+CoC_{it})^{\tau}}} \tag{11}$$

C_{it} denotes the initial investment cost per MW at $\tau = 0$, $C_{it\tau}$ represents the operation and maintenance costs per MW per year from $\tau = 1$ to $\tau = 20$ (constant) and $FLH_{it\tau}$ signifies the full load hours of the asset per year from $\tau = 1$ to $\tau = 20$ (constant). Our discount rate CoC_{it} is the technology- and time-specific cost of capital.

On the *OPEX*, we assume 2% annual inflation. We parametrise the LCOE model by using real data for full load hours , investment cost (US$ MW^{-1}) and operation and maintenance cost (US$ MW^{-1} $year^{-1}$) in Germany, and the cost of capital from our project database (see Supplementary Table 4).

For both points in time *t*, we estimate a baseline with 0% cost of capital. We separate this baseline into CAPEX, represented by the first term of Equation (12) and an OPEX component represented by the second term.

$$LCOE_{it,CoC=0} = \frac{C_{it}}{\sum_{\tau=1}^{\tau=20} FLH_{it\tau}} + \frac{\sum_{\tau=1}^{\tau=20} C_{it\tau}}{\sum_{\tau=1}^{\tau=20} FLH_{it\tau}} \tag{12}$$

We then estimate the same model with the observed cost of capital from our data r_{it} and define the change to the baseline as the financing expenditures δ_{it} of the LCOE (see Equation 13). Note that r_{it} depends on the project leverage and tax rate according to Equation 2.

$$\delta_{it} = LCOE_{it,CoC_i=r_i} - LCOE_{it,CoC=0} \tag{13}$$

As a result, we obtain three LCOE components (CAPEX, OPEX, and financing expenditures) for both technologies at both points in time, which allows us to display the changes in each component over time. We define the change in the financing expenditures, δ_{it} as Δ_i following Equation (14). Note that in Figure 6, Δ_i is denoted ‘change in financing cost’.

$$\Delta_i = \delta_{i,t=1} - \delta_{i,t=2} \tag{14}$$

We disentangle three effects that contribute to the change in financing cost, namely experience effect Δ_i^{EXP}, general interest rate effect Δ_i^{INT} and the effect resulting from lower CAPEX to be financed Δ_i^{CAPEX}. The sum of the three effects equals the total change in financing cost by definition as shown in Equation (15).

$$\Delta_i = \Delta_i^{EXP} + \Delta_i^{INT} + \Delta_i^{CAPEX} \tag{15}$$

We start with the last term and define the effect resulting from lower CAPEX as the hypothetical LCOE change with constant CoC (part 1 of Equation 16) minus the ‘pure’ CAPEX and OPEX changes (identical to the LCOE at *CoC=0*). In doing so, we define a counterfactual scenario of identical technological change (i.e., lower capital expenditure), absent changes in financing conditions. Given the mutually reinforcing mechanism of financing conditions and technological change (e.g., it is not clear that the capital expenditure would have decreased, absent improvements in financing conditions), this approach might overestimate the part of change attributed to Δ_i^{CAPEX}. As a consequence, Equation (15) provides conservative estimates of the other two effects:

$$\Delta_i^{CAPEX} = LCOE_{i,t=1,CoC[t=1]} - LCOE_{i,t=2,CoC[t=1]} - (LCOE_{i,t=1,CoC=0} - LCOE_{i,t=2,CoC=0}) \tag{16}$$

To separate the remaining part of the change in financing cost into experience effect and general interest rate effect, we use the share of the debt margin of the total change in cost of debt (*φ)*. In Equation (17), *d* denotes the difference between the value in 2017 and the value in 2000-05, and *GenIntRate* represents the general interest rate. Note that this is computing the share of the changes displayed in Figure 5.

$$\varphi_i^{DEBT} = \frac{d(DebtMargin_i)}{d(DebtMargin_i + GenIntRate)} \quad (17)$$

We assume that a similar relation holds for the equity side and stipulate $\varphi_i^{DEBT} = \varphi_i^{EQUITY} = \varphi_i$. Combining Equations (14, 16 and 17), we now can identify the experience effect Δ_i^{EXP} and the general interest rate effect Δ_i^{INT}, which are shown in Equations (18) and (19).

$$\Delta_i^{EXP} = \varphi_i(\Delta_i - \Delta_i^{CAPEX}) \quad (18)$$

$$\Delta_i^{INT} = (1 - \varphi_i)(\Delta_i - \Delta_i^{CAPEX}) \quad (19)$$

Acknowledgements

The authors thank Matthias Jäger, Michael Pahle, Friedemann Polzin, Lisa Reile and Oliver Tietjen from the INNOPATHS project, participants of the 2017 oikos Finance Academy at the University of Zurich, participants of the 41st IAEE International Conference in Groningen (2018) and members of ETH Zurich's Energy Politics Group for helpful comments on earlier drafts of the paper. This work was supported by the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract number 16.0222. The opinions expressed and arguments employed herein do not necessarily reflect the official views of the Swiss Government. This work was conducted as part of the European Union's Horizon 2020 research and innovation programme project INNOPATHS under grant agreement No. 730403.

Author contributions

T.S.S., B.S. and F.E. developed the research idea. F.E., B.S. and T.S.S. conducted the investor interviews, collected, analysed and interpreted the data, and wrote the manuscript. T.S.S. secured project funding.

Competing interests

The authors declare no competing financial or non-financial interest.

Data availability

The data displayed in Figures 1, 2 and 4 and used for calculations in Figures 5 and 6 is available upon reasonable request.

Ethics statement

No ethics approval needed

The methodology used in this paper does not require institutional ethical approval according to the guidelines set out by ETH Zurich. Informed consent was obtained from all the interviewees.

No signature requirement for informed consent

In advance of participating in the interview, respondents were provided with an information sheet describing the type of questions they would be asked. The information sheet also emphasized the anonymity of data and their right to withdraw from the study. Choosing to participate in the interview beyond that point was interpreted as informed consent.

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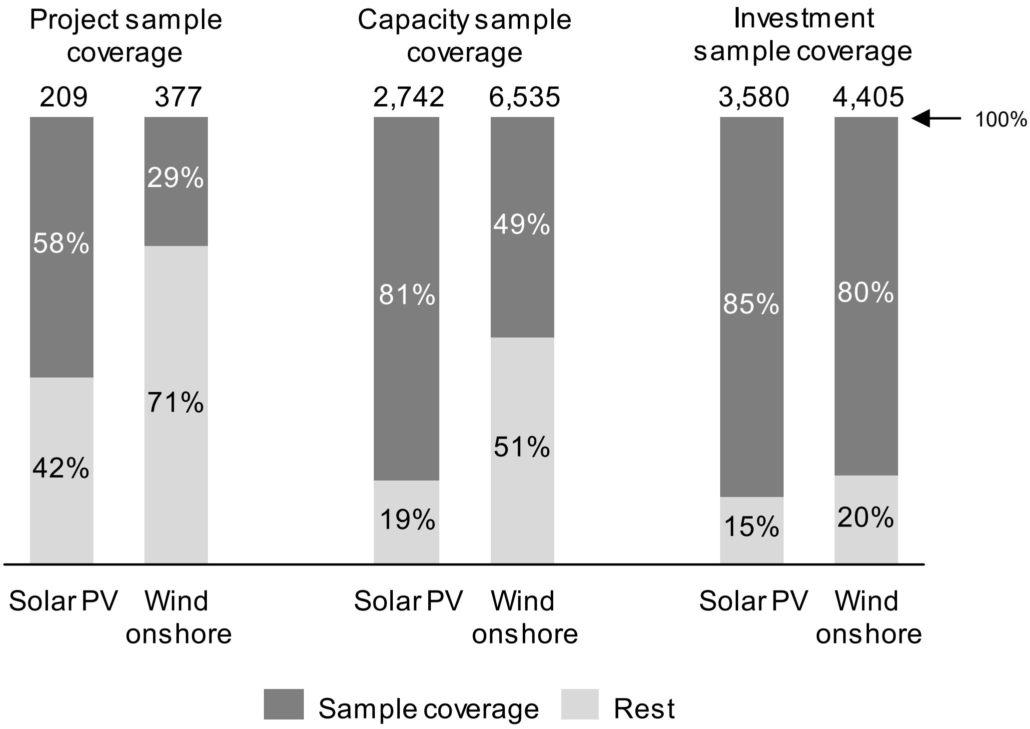
Supplementary Information

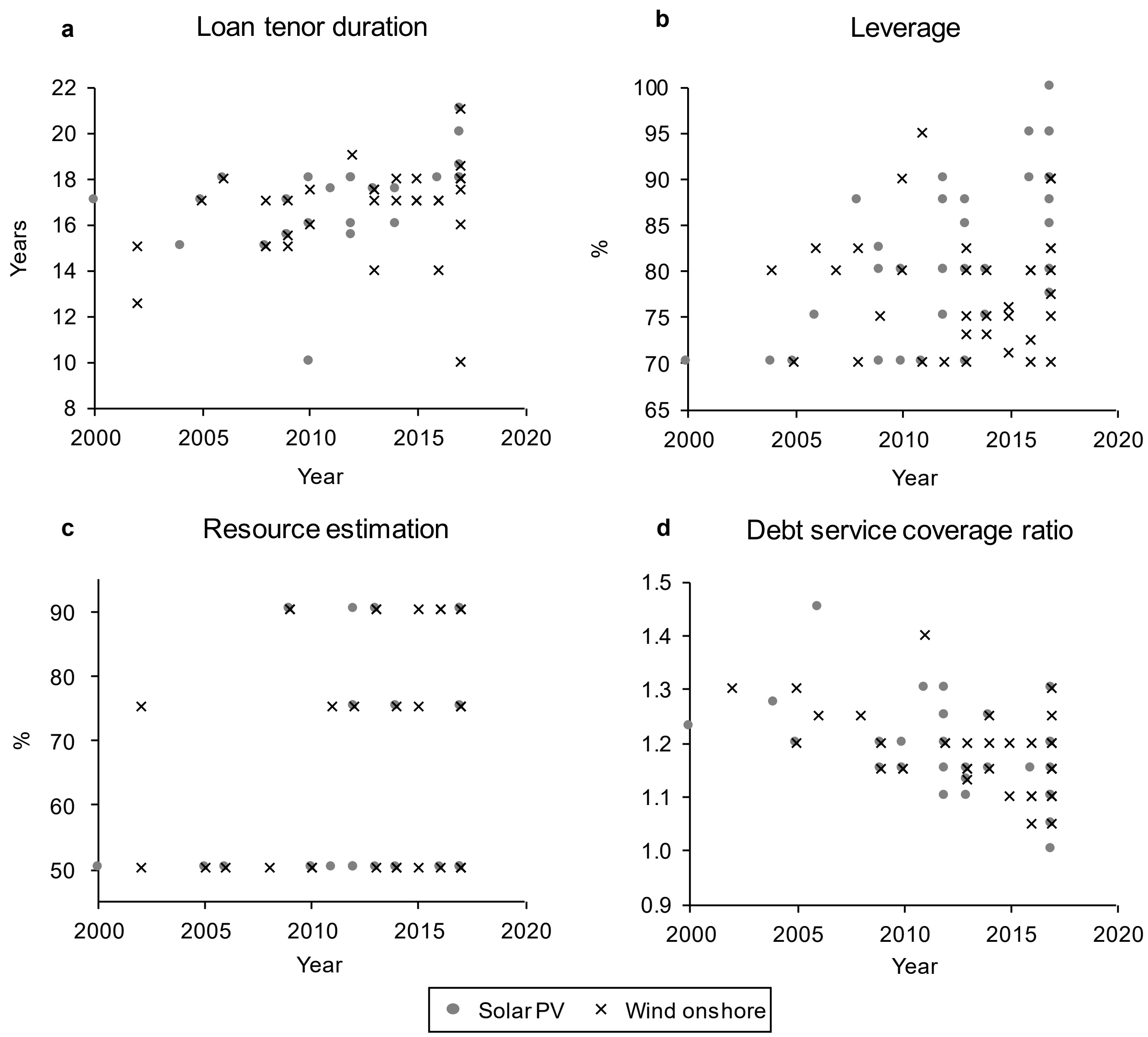
Supplementary Note 1: Key terms of project finance

In project finance, each project is a separate legal entity, set up for the project's lifetime, often called a special purpose vehicle (SPV). The project sponsors hold equity in the SPV, and banks typically provide loans (i.e., debt) to the SPV. In this paper, we call both project sponsors and banks *investors*. The expected returns to project sponsors are called *cost of equity*, and the interest to be paid on the loans is called *cost of debt*. The relative shares of debt and equity in a project define the leverage or capital structure of the SPV. Loan providers usually have no recourse beyond the project, which means the project's risk profile translates directly to the cost of debt. Consequently, the cash flows generated by the SPV must cover operating costs and the debt service (i.e., capital repayment and interest)[1]. Any remaining cash flows go to the project sponsors and constitute their return on the investment. Therefore, equity investors also are concerned about a project's ability to service outstanding debt. The common metric to assess debt service is the debt service coverage ratio (DSCR), which serves as a direct measure of project risk (see Supplementary Table 1). Moreover, the SPV's capital structure usually also is an indication of project risk because more debt increases the debt service (just as a higher cost of debt does). As per convention, we analyse the financing conditions of SPVs at the beginning of projects, i.e., the point when investors make their investment decisions. Contrary to corporate finance, project finance directly ties the cost of capital to project risk[1,2] – providing a unique setting in which to study the dynamics of renewable energy financing conditions. Because project finance conditions are not quoted publicly, it is necessary to elicit data from renewable energy investment professionals.

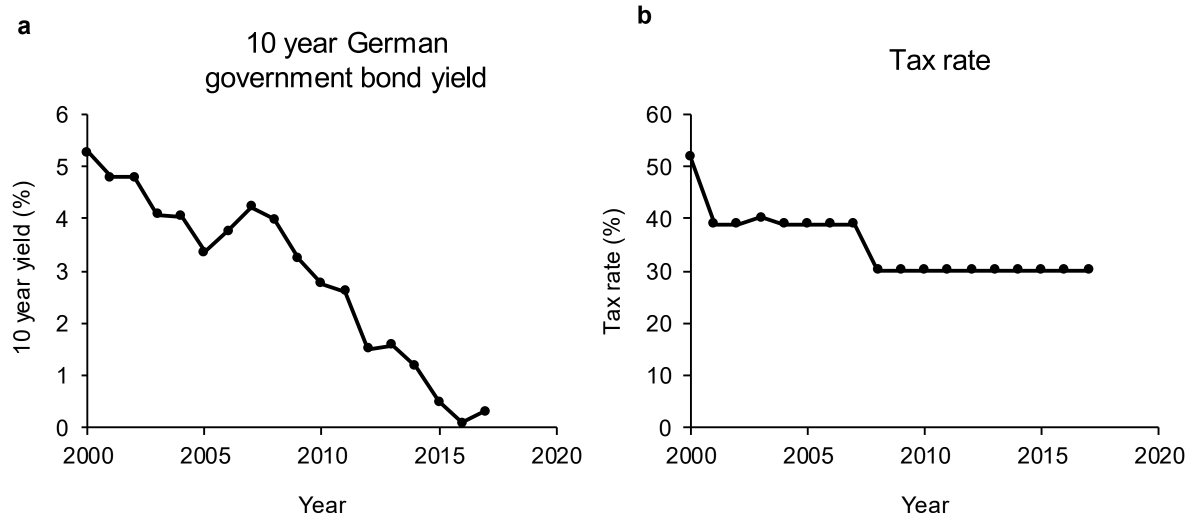
Supplementary Figures



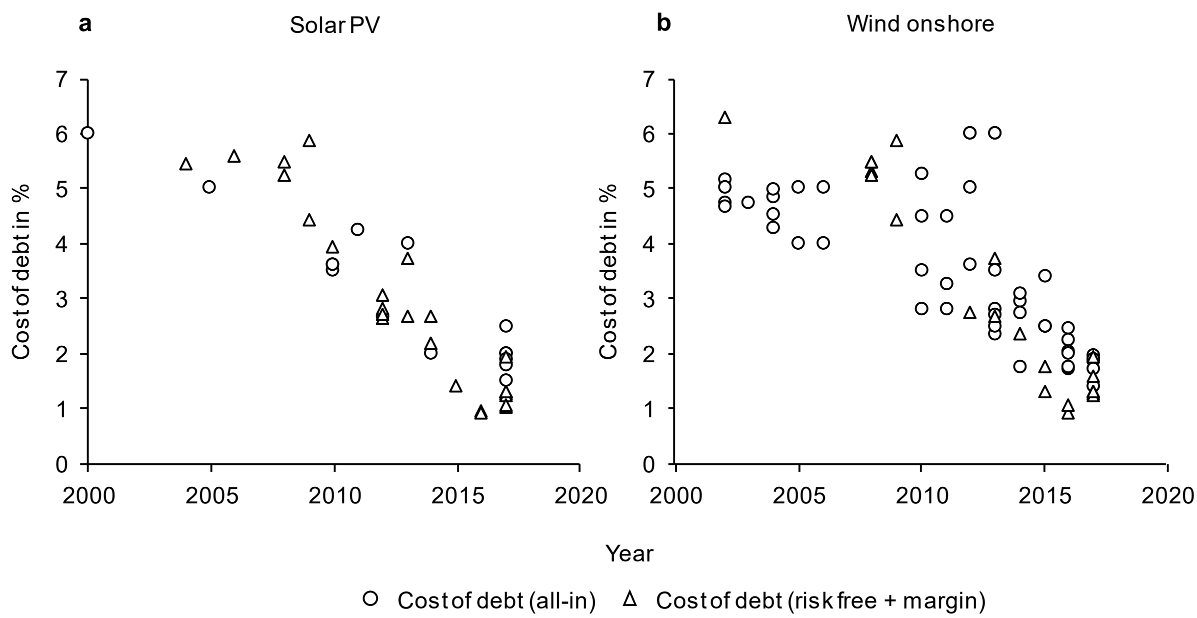
Supplementary Figure 1: Market share of our data providers. Sample coverage is shown with regards to all deals recorded in the BNEF asset database between 2000 and 2017. We calculate the sample coverage over the total of deals, where a lead debt arranger is specified. BNEF provides at least one lead debt arranger for 45% of solar PV investments and 42% of wind onshore investments.



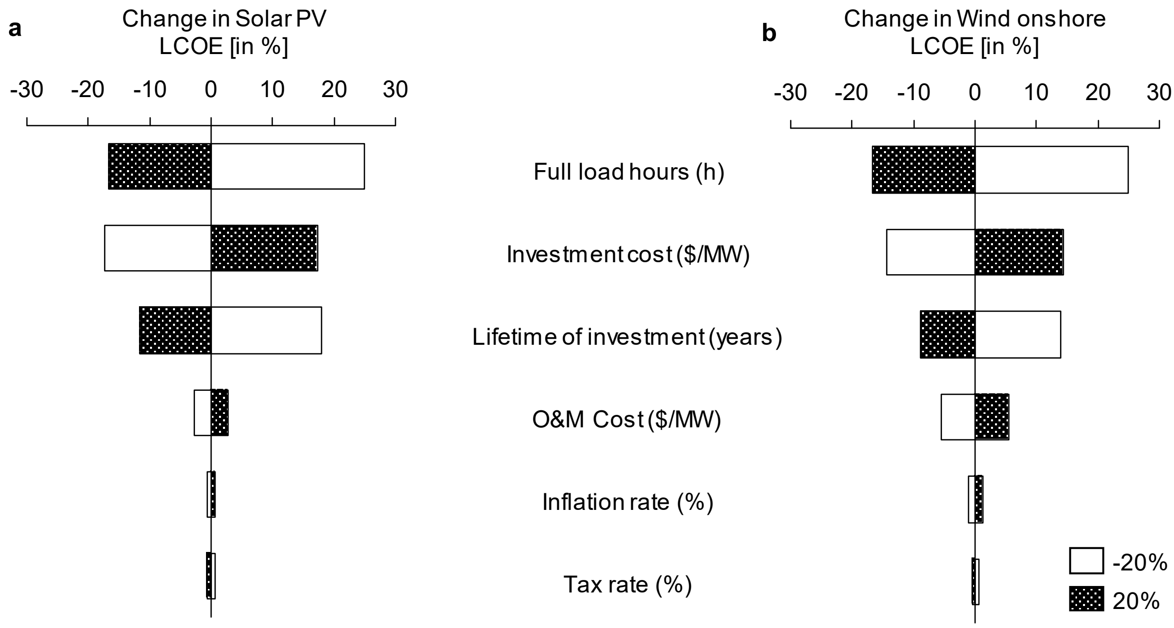
Supplementary Figure 2: Financial deal characteristics. **a**, Loan tenors (N = 70) increased over time. **b**, Leverage (N = 74) increased for solar PV and remained relatively constant for wind onshore. **c,** the resource estimation (percentile of the estimated distribution) has remained split between p50 (median) and p90 (risk-averse) for both technologies (N = 61). **d**, The debt service coverage ratio (N = 71) decreased for both technologies.



Supplementary Figure 3: Economic variables. Government bond yields decreased from over 5% to 0.31% over the period of our sample (**a**)[3]. The corporate tax rate has fallen from 52% to 30%, making debt comparatively more expensive (**b**)[4].



Supplementary Figure 4: Data validity check comparing the reported all-in cost of debt vs. 'synthetic' cost of debt resulting from reported debt margins adding the yield of a 10 year German government bond (risk free). **a**, Solar PV projects (N = 42), of which 15 all-in and 27 'synthetic'. **b**, Wind onshore projects (N = 73), of which 51 all-in and 22 'synthetic'.



Supplementary Figure 5: LCOE sensitivity analysis for solar PV (**a**) and wind onshore (**b**). The figure depicts percent changes in the LCOE for both technologies given a +/- 20% change in one of the LCOE variables (all other variables stay remain constant). See Table 4 in the Supplementary Information for the values.

Supplementary Tables

Supplementary Table 1: Definitions of financial terms.

Term	Definition
Capital expenditure (CAPEX)	The initial expenditure (i.e. investment) into the RET generation asset.
Cost of capital (CoC)	The weighted average cost of capital (often denoted WACC) of a project, calculated according to Equation (2).
Cost of debt	Interest payments on the debt raised to finance a project.
Cost of equity	Dividends payments (i.e. return) to project shareholders.
Debt margin	The project specific margin on top of the refinancing rate of the debt provider (e.g., bank).
Debt service coverage ratio (DSCR)	A measure of project cash flows available to pay debt obligations, namely the principal repayment and interest rate payments.
Financing conditions	The wider financial conditions of a project including among others CoC, DSCR, and loan tenor.
Financing cost	The total cost of capital service, including debt service (i.e. principal repayment and interest rate payments) and returns to equity.
Investment cost	The initial investment cost of a RET generation. Used interchangeably with capital expenditure.
Leverage	The project capital structure, i.e. the share of debt of the total investment sum.
Loan tenor	The time period for repayment of the loan.
Operating expenditure (OPEX)	Expenditures to operate the RET generation assets, occurring throughout the asset lifetime (if operated).
P value	The percentile value of the distribution of solar irradiation or wind speed predictions used for project assessment. Calculating project returns on a p90 value means to take the 90th percentile of the predicted distribution and represents a more conservative approach than for example p50 (median).

Supplementary Table 2: Summary statistics. Counting all project where we have a value for at least one of the following variables: Cost of debt, cost of equity, leverage, cost of capital, loan tenor, and DSCR, our sample covers 48 solar PV and 85 wind onshore projects between 2000 and 2017 (N = 133). If we limit the sample to projects for which we have data on the cost of capital only (cost of debt, cost of equity or cost of capital), our sample includes 43 solar PV and 78 wind onshore projects (N = 121).

	N	Mean	Std. Dev.	Min	Max
K_D	112	3.18	1.57	0.89	6.28
K_E	66	7.07	2.13	3.25	14
Leverage (debt share)	74	80	7.75	70	100
Debt margin	49	1.25	0.43	0.7	2.65
Cost of capital	57	3.20	1.59	0.59	9.50
Loan tenor	70	16.89	2.11	10	21
DSCR	71	1.18	0.08	1	1.45

Supplementary Table 3: Full interview sample (N = 41)

ID	Interview type	Current organisation	Current position	Based in	RET investment experience (years)	Sex	Age range
1	Structured	Debt provider	Head of Division Energy & Utilities	Germany	12	M	25-45
2	Structured	Debt provider	Vice President	Germany	28	M	45-65
3	Structured	Debt provider	Associate Director Project Finance & Capital Advisory	Germany	7	M	25-45
4	Structured	Debt provider	Associate Director Infrastructure & Power Project Finance	Germany	9	M	25-45
5	Structured	Debt provider	Executive Director Project Finance Renewable Energies	Germany	21	M	45-65
6	Structured	Debt provider	Associate Director Global Infrastructure Debt	United Kingdom	5	F	25-45
7	Structured	Debt provider	Head Renewable Energies	Germany	27	M	45-65
8	Structured	Debt provider	Project Finance Analyst	Germany	11	M	25-45
9	Structured	Debt provider	Vice President Corporates & Small Business Project Finance	Germany	11	M	45-65
10	Structured	Debt provider	Director Structured Finance Power & Renewables	The Netherlands	11	M	45-65
11	Structured	Debt provider	Director Structured Finance Utilities, Power & Renewables	The Netherlands	11	M	25-45
12	Structured	Debt provider	Senior Manager Structured Finance Renewable Energy	Germany	19	M	45-65
13	Structured	Debt provider	Director Project & Structured Finance Utilities, Power and Renewables	Italy	11	F	25-45
14	Structured	Debt provider	Director Corporate Strategy	The Netherlands	19	M	40-65
15	Structured	Debt provider	Head of Renewable Energies	Germany	23	M	40-65
16	Structured	Debt provider	Head of Project Finance Origination Renewable Energies	Germany	8	M	45-65
17	Structured	Debt provider	Managing Director Project & Acquisition Finance	United Kingdom	12	M	25-45
18	Structured	Equity provider*	Head Risk Advisory	Germany	13	M	45-65
19	Structured	Equity provider*	CEO	Germany	10	M	45-65
20	Structured	Equity provider*	Founder and CEO	Germany	5	M	25-45
21	Structured	Equity provider	Principal	Switzerland	5	M	25-45
22	Structured	Equity provider	Partner	Switzerland	9	M	45-65
23	Structured	Equity provider	Director Infrastructure Equity Investment Team	Germany	12	M	45-65
24	Structured	Equity provider	Vice President Renewables	Switzerland	3	M	25-45
25	Structured	Equity provider	CIO	Germany	2	M	25-45
26	Structured	Equity provider	CEO	Germany	2	M	25-45
27	Structured	Equity provider	Associate Director Energy & Cleantech	France	12	M	25-45
28	Structured	Equity provider	Associate	United Kingdom	18	M	25-45
29	Structured	Public actor	Head Energy Services	Switzerland	12	M	25-45
30	Structured	Public actor	Deputy Head Energy Management	Switzerland	3	M	25-45
31	Structured	Public actor	CEO	Switzerland	7	M	45-65

32	Structured	Public actor	Head Portfolio and Asset Management Renewable Energies	Switzerland	8	M	25-45
33	Structured	Public actor	Vice President Origination and Structuring	Germany	6	M	25-45
34	Exploratory	Equity provider	Founding Partner	Switzerland	18	F	45-65
35	Exploratory	Equity provider	Investments Director	United Kingdom	12	M	25-45
36	Exploratory	Equity provider*	Head Risk Advisory	Germany	13	M	45-65
37	Exploratory	Equity provider	Partner	Switzerland	9	M	45-65
38	Exploratory	Equity provider	Principal	Switzerland	5	M	25-45
39	Exploratory	Other (former researcher)	Head Hybrid Power Solutions	Germany	12	M	25-45
40	Exploratory	Public actor	Senior Investment Manager	Norway	11	M	45-65
41	Exploratory	Public actor	Economist	Luxemburg	15	M	25-45

* = Acts as advisor for equity investors

Note: For age, only ranges given to protect anonymity of interviewees

Supplementary Table 4: LCOE model parameters

	Solar PV		**Wind onshore**	
Parameters	2000-05	2017	2000-05	2017
Inflation	2%	2%	2%	2%
Full load hours p.a.[5,6]	1051	1051	1500	2716
Investment cost US\$ MW^{-1} (CAPEX)[7]	6.37m	1.05m	1.60m	2.00m
Operation and maintenance cost US\$ MW^{-1} $year^{-1}$ (OPEX)[6,8]	8’000	8’000	38’000	38’000
Asset lifetime	20	20	20	20
Cost of capital	5.1%	1.6%	4.5%	1.9%

Supplementary Table 5: Solar PV experience rate estimation and robustness checks. All regressions are calculated using OLS with robust standard errors and all variables are in log. For each specification, we show a version without and a version with investor fixed effects. InvUNEP denotes the cumulative global investment data from UN Environment (columns 1 and 2), InvEU denotes cumulative European investment (columns 3 and 4), InvBNEFxIRENA denotes the alternative measure for cumulative global investment using data from BNEF on investment cost per MW and data from IRENA on capacity (columns 5 and 6). The resulting minimum and maximum experience rates are shown in Supplementary Table 7. For details on the variables, see Methods.

	(1)	(2)	(3)	(4)	(5)	(6)	(1)	(2)	(3)	(4)	(5)	(6)	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Log(debt margin)						Log(dscr-1)						Log(loan tenor)					
Log(InvUNEP)	-0.162***	-0.149***					-0.209***	-0.257***					0.0376**	0.0585**				
	(0.0532)	(0.0362)					(0.0744)	(0.0638)					(0.0170)	(0.0224)				
Log(InvEU)			-0.155**	-0.147***					-0.186**	-0.215***					0.0276*	0.0479**		
			(0.0567)	(0.0451)					(0.0699)	(0.0543)					(0.0152)	(0.0200)		
Log(InvBNEFxIRENA)					-0.164***	-0.151***					-0.226***	-0.273***					0.0403**	0.0623**
					(0.0511)	(0.0356)					(0.0759)	(0.0609)					(0.0171)	(0.0226)
Constant	1.194***	1.693***	2.042***	2.532***	1.162***	1.662***	-0.588	-0.206	0.335	0.746	-0.539	-0.163	2.598***	2.434***	2.501***	2.231***	2.591***	2.423***
	(0.350)	(0.239)	(0.690)	(0.556)	(0.322)	(0.227)	(0.429)	(0.497)	(0.804)	(0.749)	(0.416)	(0.468)	(0.117)	(0.157)	(0.187)	(0.256)	(0.114)	(0.152)
Investor fixed effects	no	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no	yes
Observations	27	27	27	27	27	27	35	35	35	35	35	35	36	36	36	36	36	36
R-squared	0.287	0.850	0.204	0.801	0.284	0.847	0.162	0.696	0.115	0.634	0.167	0.697	0.104	0.398	0.050	0.319	0.107	0.402

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplementary Table 6: Wind onshore experience rate estimation and robustness checks. All regressions are calculated using OLS with robust standard errors and all variables are in log. For each specification, we show a version without and a version with investor fixed effects. InvUNEP denotes the cumulative global investment data from UN Environment (columns 1 and 2), InvEU denotes cumulative European investment (columns 3 and 4), InvBNEFxIRENA denotes the alternative measure for cumulative global investment using data from BNEF on investment cost per MW and data from IRENA on capacity (columns 5 and 6). The resulting minimum and maximum experience rates are shown in Supplementary Table 7. For details on the variables, see Methods.

	(1)	(2)	(3)	(4)	(5)	(6)	(1)	(2)	(3)	(4)	(5)	(6)	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Log(debt margin)						Log(dscr-1)						Log(loan tenor)					
Log(InvUNEP)	-0.164**	-0.162***					-0.261***	-0.283***					0.0430*	0.0532**				
	(0.0633)	(0.0472)					(0.0594)	(0.0936)					(0.0253)	(0.0254)				
Log(InvEU)			-0.254**	-0.254***					-0.423***	-0.459**					0.0688*	0.0866**		
			(0.0982)	(0.0750)					(0.0992)	(0.161)					(0.0401)	(0.0377)		
Log(InvBNEFxIRENA)					-0.182***	-0.178***					-0.280***	-0.310***					0.0449	0.0567*
					(0.0638)	(0.0423)					(0.0646)	(0.0964)					(0.0280)	(0.0288)
Constant	1.250***	1.789***	3.272**	3.819***	1.292***	1.816***	-0.123	-0.0273	3.315***	3.703*	-0.118	0.0186	2.531***	2.472***	1.976***	1.769***	2.538***	2.473***
	(0.416)	(0.317)	(1.196)	(0.910)	(0.392)	(0.264)	(0.344)	(0.651)	(1.161)	(1.974)	(0.350)	(0.628)	(0.154)	(0.172)	(0.474)	(0.464)	(0.159)	(0.183)
Investor fixed effects	no	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no	yes
Observations	22	22	22	22	22	22	36	36	36	36	36	36	34	34	34	34	34	34
R-squared	0.212	0.913	0.209	0.915	0.235	0.925	0.218	0.636	0.224	0.645	0.222	0.648	0.089	0.746	0.091	0.753	0.083	0.743

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplementary Table 7: Experience rate robustness checks. The table indicates minimum and maximum values for the experience rates across all model specifications shown in Supplementary Tables 5 and 6.

	Solar PV		**Wind onshore**	
	Min	Max	Min	Max
Debt margin	10%	11%	11%	16%
DSCR	12%	17%	17%	27%
Loan tenor	-2%	-4%	-3%	-6%

Supplementary References

1. Gatti, S. *Project finance in theory and practice : designing, structuring, and financing private and public projects*. (Academic Press, 2013).
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Paper 4

Renewable energy investment risk : An investigation of changes over time and the underlying drivers

Citation: Egli, F. (2020). Renewable energy investment risk : An investigation of changes over time and the underlying drivers. *Energy Policy*, *140*, 111428. https://doi.org/10.1016/j.enpol.2020.111428

Contributions: F.E. developed the research idea, collected and analysed the data and wrote the paper.

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Abstract

Building an energy system compatible with the Paris Agreement requires large-scale investment in renewable energy technologies (RET). Designing effective energy policies, therefore, requires an understanding of the dynamics of RET investment risk. This study draws on RET project data and 40 interviews with investors in Germany, Italy and the United Kingdom. We identify the five most relevant RET investment risk types (curtailment, policy, price, resource and technology), show their relative importance over time and use a network analysis of interview transcripts to identify the drivers behind the observed changes. We show that risk premiums and investment risk have declined for solar photovoltaics and onshore wind technologies in all three countries. Increasing technology reliability at a lower cost, data availability, better assessment tools and credible and stable policies were crucial elements of this declining investment risk. While policy and technology risks have become relatively less important over time, curtailment and price risks are becoming relatively more important. From these insights, we derive recommendations for policymakers aiming to accelerate the transition towards a Paris-compatible energy system.

Energy Policy 140 (2020) 111428

Contents lists available at ScienceDirect

Energy Policy

journal homepage: http://www.elsevier.com/locate/enpol

Renewable energy investment risk: An investigation of changes over time and the underlying drivers

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ARTICLE INFO

Keywords:
Renewable energy
Energy finance
Investment risk
Public policy

ABSTRACT

Building an energy system compatible with the Paris Agreement requires large-scale investment in renewable energy technologies (RET). Designing effective energy policies, therefore, requires an understanding of the dynamics of RET investment risk. This study draws on RET project data and 40 interviews with investors in Germany, Italy and the United Kingdom. We identify the five most relevant RET investment risk types (curtailment, policy, price, resource and technology), show their relative importance over time and use a network analysis of interview transcripts to identify the drivers behind the observed changes. We show that risk premiums and investment risk have declined for solar photovoltaics and onshore wind technologies in all three countries. Increasing technology reliability at a lower cost, data availability, better assessment tools and credible and stable policies were crucial elements of this declining investment risk. While policy and technology risks have become relatively less important over time, curtailment and price risks are becoming relatively more important. From these insights, we derive recommendations for policymakers aiming to accelerate the transition towards a Paris-compatible energy system.

1. Introduction

Redirecting investment flows to low-carbon assets and technologies is paramount to achieving the goals of the Paris Agreement (IPCC, 2014; Polzin, 2017). To achieve a Paris-compatible energy system, an estimated additional annual $536 billion, as well as a shift in investment patterns, is necessary to supplement the current policies from 2016 to 2050 (McCollum et al., 2018). The share of low-carbon investments in the total supply-side energy investment must grow from around 35% in 2015 to just below 80% by 2050. Among low-carbon energy generation technologies, solar photovoltaics (PVs) and wind are set to become the (combined) largest source of electricity in a Paris-compatible energy system by 2030 (OECD/IEA and IRENA, 2017).

To reach the levels of investment in renewable energy technologies (RET) required by the Paris Agreement, these technologies must become cost-competitive with fossil fuel–based technologies (FFT). Because RETs are more capital intensive than FFTs, reductions in the financing cost (the cost of capital) for RETs increase their cost competitiveness versus FFTs (Hirth and Steckel, 2016; Ondraczek et al., 2015; Schmidt, 2014). Recent research shows that the cost of capital for RETs has decreased over time (Donovan and Li, 2018; Ecofys, 2016; Egli et al., 2018), which, in the case of solar PV and onshore wind in Germany, is partly due to lower risk premiums (measured via debt margins) (Egli et al., 2018). Economic theory predicts a positive link between risk and return (Merton, 1973), indicating that observed declines in RET risk premiums should coincide with a change in investment risk. Low investment risk, in turn, attracts private capital on a large scale, as many studies have found investment risk to be a main barrier to RET deployment (Energiewende, 2018; Painuly, 2001; Steggals et al., 2017; Waissbein et al., 2013), specifically for large institutional investors (Kaminker and Stewart, 2012). While there is extensive literature on RET investment risk, there is little to no empirical data on the dynamics of RET investment risk over time and the drivers of that risk. This is surprising given that investment risk evolves over time as technologies develop (Kitzing et al., 2018) and the effectiveness of policies aiming to attract RET investments depends largely on their ability to reduce investment risk (Komendantova et al., 2019; Polzin et al., 2019; Schinko and Komendantova, 2016).

The empirical literature on RET investment risk can be divided into two streams. The first aims to develop a better understanding of investor behaviour by shedding light on trade-offs, decision metrics (including risk) and biases. For example, these studies show that addressing investment risk tends to be more effective in inducing investment than increasing returns (Lüthi, 2010) and that, besides risk, investors are also

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https://doi.org/10.1016/j.enpol.2020.111428
Received 26 April 2019; Received in revised form 3 February 2020; Accepted 9 March 2020
Available online 31 March 2020
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driven by portfolio effects, a priori beliefs and path dependence (Masini and Menichetti, 2012; Wüstenhagen and Menichetti, 2012). The literature also shows that risk-return profiles are strongly affected by policy risk, but cross-country diversification can mitigate this risk (Gatzert and Vogl, 2016). Policy risk, in turn, is lower when policymakers have more autonomy from the political process (Holburn, 2012), and it differs according to the chosen policy instrument (Kitzing, 2014).

The second stream of research concerns empirical risk elicitation. These studies typically focus on a technology and/or a country and determine the most important investment risks through either choice experiments or surveys and interviews with investors. In general, they show that policy risk is important in solar PV (Karneyeva and Wüstenhagen, 2017) and onshore wind investment decisions (Steggals et al., 2017) in the European Union (Angelopoulos et al., 2016), as well as in less developed countries (Komendantova et al., 2012; Waissbein et al., 2013). Business-related risks such as financial risk (e.g., access to capital) and market risk (e.g., future power prices) are also important in mature markets like Western Europe, North America and Australia (Economist Intelligence Unit, 2011; Leisen et al., 2019).

In sum, there is evidence of the importance of risk in the investment decision. The literature also provides guidance to policymakers in specific countries regarding the relative importance of different types of risk for a given technology. However, there is no data on the evolution of investment risk over time. While Egli et al. (2018) established the dynamics of financing conditions over time, they did not evaluate this concept in markets other than Germany. Moreover, their study does not provide evidence as to whether the observed changes in risk margins were the result of changing investment risks or other factors such as better operational efficiency of banks or increased competition. This paper, therefore, proposes the following research question:

Are there similar risk premium dynamics in markets other than Germany, and what are their drivers?

Understanding the dynamics of RET investment risk and its implications for financing conditions is important for at least two reasons. First, it brings more clarity to the drivers of changes in financing conditions, therefore potentially aiding policymakers to speed up the decrease in RET financing costs. Second, it demonstrates how RET investment risks may be affected by potential RET support policy phase-outs (Karneyeva and Wüstenhagen, 2017; Pahle and Schweizerhof, 2016) and may impact the cost competitiveness of RETs in consequence.

This paper follows three analytical steps: First, it identifies the most important components of RET investment risk (risk types) using the literature on investment risk and exploratory investor interviews. Second, it describes changes in risk premiums in Germany, Italy and the United Kingdom (UK) using project-level data and ranks the identified risk types over time based on investor interviews. Finally, this paper draws on the extensive experience of 40 RET investors to identify drivers of change and link those drivers to risk types using coded interview transcripts. The remainder of this paper is organised as follows: Section 2 introduces the research case and describes the methods used. Section 3 presents the results. Section 4 discusses research and policy implications.

2. Research design

2.1. Case selection

In this study, the case selection was based on three dimensions: country, technology and project phase. To analyse changes in investment risk, we chose typical (or representative) cases, which allow us to study a phenomenon in detail (Seawright and Gerring, 2008). We focused on countries that were early adopters of RETs – namely Germany, Italy and the UK. From 2000 to 2005, these three countries accounted for over one-third of the cumulative global wind capacity, and from 2004 to 2014, the same was true for solar PV (IRENA, 2018a). Fig. 1 shows the cumulative installed capacity and annual clean energy investment for each country and denotes the years in which we elicit investment risks: 2009, 2013 and 2017. The choice of years was motivated by three reasons. First, the lion share of investments and capacity deployments happened from 2009 onwards.[1] Second, we chose to elicit data at three points in time with equal intervals to infer dynamics over time. Third, by starting in 2009, we circumvent the 2007–08 financial crisis and we cover a period of relatively stable interest rates (see Figure A1 in the Appendix). Over this period, the regulatory environments of these countries differed, meaning that each country had different risk exposure from an investor's perspective (Mitchell et al., 2006). While the focus of this paper is not on comparing policies, we have used this variation to identify the effects on policy risk. Germany serves as the base case, with a fixed-price RET support policy that was never changed retroactively. Italy used a fixed-price RET support policy, too, but it applied a retroactive policy change to large-scale solar PV in 2014 (Ramirez et al., 2017). The UK used a more market-based support policy by relying on quotas, tradable certificates and contracts for difference[2] (Lipp, 2007; Mitchell and Connor, 2004).

The study focuses on solar PV and onshore wind technologies, the most deployed non-hydro RETs (IRENA, 2018a). These technologies differ regarding their complexity of design and operation and their resource volatility (i.e., solar irradiation versus wind speed), which may result in different investment risk profiles. For example, wind turbines are complex products consisting of many different (incl. moving) components, which means that a turbine needs to be adapted to local circumstances (Schmidt and Huenteler, 2016). Again, this study is not of a comparative nature, but it uses the technology differences to identify risk types that vary by technology.

Lastly, RET project phases typically include the planning and development phase, the construction phase and the operation phase (Breitschopf and Pudlik, 2013; Ecofys, 2016). Achieving the goals of the Paris Agreement will require tapping large pools of long-term capital. Large institutional investors typically seek low-risk and long-term projects (Nelson, 2015), and therefore, they tend to invest in commissioned and ready-to-operate (or operating) RET projects. In other words, they usually do not take planning and development or construction risks. For this reason, the present paper focuses only on the operation phase of RET projects.

2.2. Methods

The study draws on investor interviews conducted in English or German under Chatham House rule[3] in person or over the phone between September 2017 and January 2018 (see Table A1 in the Appendix for the interview questions). Each interview lasted approximately 60 min and was transcribed verbatim. The interview sample includes 40 investors, of which 17 are private-sector debt providers (13 commercial banks and 4 investment banks), 15 are private-sector equity providers, 7 are public-sector actors (4 public utilities and 3 public investment

[1] Onshore wind capacities increased by 96%, 181% and 163% for Germany, Italy and the UK respectively between 2009 and 2017. For solar PV, the increase amounts to 301% for Germany and for Italy and the UK the increases were 15 and to 350-fold.

[2] Contracts for difference (CfD) protect developers from wholesale price volatility. Typically, a developer receives a flat rate per unit of electricity generated. If that rate is above the wholesale electricity price, the developer receives the difference. If the rate is below the wholesale electricity price, the developer pays back the difference. Thereby, CfDs provide revenue certainty to the developer and the investor.

[3] The Chatham House rule states that "participants are free to use the information received, but neither the identity nor the affiliation of the speaker(s) … may be revealed" (Chatham House, 2002).

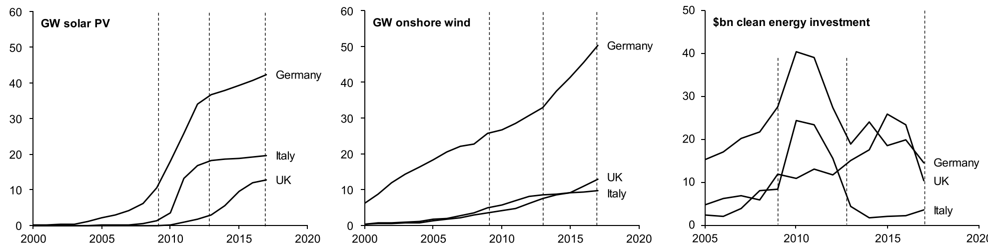

Fig. 1. Cumulative installed solar PV and onshore wind capacity and annual clean energy investment (in $USD billion) for Germany, Italy and the UK. Sources (BloombergNEF, 2018; IRENA, 2018b).

banks) and one is a consultant (see Table A2 in the Appendix for a full list of the interviewees[4]). We use a theoretical sampling strategy to identify the 40 investors. On the one hand, we focus on investors with RET investment experience over time (11 years on average); on the other hand, we balance our sample to reflect the different sources of finance (17 debt providers versus 15 equity providers and 7 public sector actors) and the country and technology scope (34 investors with onshore wind experience versus 30 with solar PV experience, see Figure A2 in the Appendix). In practise the sampling comprised several steps. First, we screened the Bloomberg New Energy Finance database – currently the most comprehensive RET asset finance database, on which key reports, such as the Clean Energy Investment Trends are based (BloombergNEF, 2020) – to identify the debt and equity providers with a prominent role in onshore wind and solar PV financing in Germany, Italy and the UK. Subsequently, we used our network to contact as many of the most important debt and equity providers directly via personal e-mail. Moreover, we used snowball sampling to reach out to more investors by asking each interviewee for relevant further actors according to the scope of this study.

This study follows three methodological steps, illustrated in Fig. 2. Additionally, two workshops with RET investors and academics in Utrecht (September 2017) and Berlin (April 2018) helped refine the selection of risk types in the first step and triangulate the findings of the second. Triangulation refers to the use of different but complementary data sources in a mixed methods research design (Creswell and Plano Clark, 2011). Here, we use the term to refer to the use of different data sources – specifically the use of qualitative evidence to understand and augment the quantitate data – to corroborate the findings and increase their validity. In the first step, we identified the most important RET investment risk types, compiled a long list of RET investment risks from the literature (see Table A3 in the Appendix) and used the exploratory interviews (N = 4) to identify the most relevant risk types given the country, technology and timeframe of the study. To determine the relevant literature, we conducted four Scopus searches of journal articles only,[5] scanned abstracts for relevance[6] and included further papers and grey literature based on information obtained in the literature. To select the relevant risks from the long list, we tested several different categorisations and discussed whether they were mutually exclusive and collectively exhaustive in a team of three researchers (Morgan et al., 2000). Once we selected the risk types, we defined them together with the exploratory interviewees.

In the second step, we used the identified risk types and asked the investors to rank them for 2009, 2013 and 2017 in order to identify their relative importance. Following the literature on retroactive sense-making biases, we evoked an anchoring event for 2009, 2013 and 2017 to make it easier for the interviewees to remember the point in time (Choi and Pak, 2005). We showed the investors our definition for each risk type (as shown in Table 1). Depending on their investment experience, the investors were free to indicate whether their assessment was applicable to both technologies in all countries or differed according to technology or country. We aggregated the rankings by country and technology using the Borda count method (Emerson, 2013).[7] We also used the investor contacts established through our interviews to elicit project-level financing data for solar PV and onshore wind projects. This data was collected using the same method employed in Egli et al. (2018) – namely, investors named utility-scale projects corresponding to a reference project[8] that they had realised or analysed in the past and provided project-specific financing data. In addition to the project-level financing data, we asked investors about the general RET investment risk by letting them choose the most comparable asset class to a RET investment in 2009, 2013 and 2017 from five options for each year and technology. We use these assessments to verify and complement the findings from the financing data.

In the third and final step, we used a network analysis of the interview transcripts to identify the drivers of changes in investment risk. Interviewees were free to name and explain the main drivers that led to the changes in investment risk. Following Eisenhardt (1989), we continued holding interviews until no additional insights were provided. All interviews (N = 40) were transcribed verbatim. We used grounded theory to code the data and categorise the drivers. Glaser described coding as "a process that gets the analyst off the empirical level by fracturing the data, then conceptually grouping it into codes that then become the theory, which explain what is happening in the data" (cited in Walker and Myrick, 2006). Using the software MaxQDA, we coded all interview transcripts according to the risk involved, the country (if

[4] We contacted the same set of investors as in Egli et al. (2018) with one exception. The described sampling strategy is therefore identical to Egli et al. (2018).

[5] Search term 1: TITLE-ABS-KEY ("renewable energy" AND "investment risk" ANDNOT model) AND (LIMIT-TO (SRCTYPE, "j")) (N = 39); search term 2: TITLE-ABS-KEY ((solar OR pv OR wind) AND ("investment risk" OR "RE risk") AND ("risk factor" OR "risk type")) AND (LIMIT-TO (SRCTYPE, "j")) (N = 5); search term 3: TITLE-ABS-KEY (infrastructure AND "investment risk" AND ("risk factor" OR "risk type")) AND (LIMIT-TO (SRCTYPE, "j")) (N = 3); search term 4: TITLE-ABS-KEY ((solar OR pv OR wind) AND ("investment risk" OR "RE risk") AND ("risk assessment" OR "risk management")) AND (LIMIT-TO (SRCTYPE, "j")) (N = 18).

[6] We excluded articles that consider only one investment risk, only one technology (except for solar PV and wind) or only non-investment grade countries.

[7] The Borda count method allocates points to an option based on the number of options ranked below (see Emerson, 2013). Hence, if there was a choice between five risk types, the risk ranked first by an investor received five points, whereas the risk ranked last received one point. The method was chosen for its straightforward interpretation and its wide use (e.g., in US sport awards). One caveat of the method is its susceptibility to strategic voting. If a respondent ranks only his/her favourite option first and leaves the other spots blank, the results are biased. In this study, the interviewed investors did not know the counting method and they had no strategic reason to rank only a subset of risks. Strategic voting is hence highly unlikely.

[8] The reference project specifies an investment sum of approximately €20 million and standard established technology, which ensures that the sources of finance are established debt and equity investors (e.g., excluding early stage debt or venture capital).

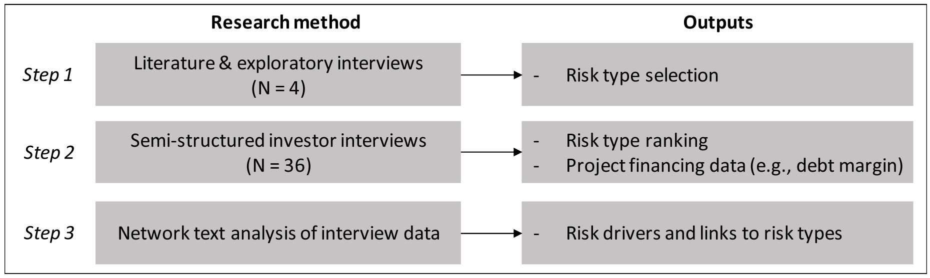

Fig. 2. Methodological approach in three steps.

Table 1
Definitions of risk types.

Risk type	Definition
Curtailment risk	The risk of lower revenues due to unexpected curtailment (e.g., grid bottlenecks).
Policy (reversal) risk	The risk of lower revenues due to a retroactive change in a cornerstone RET policy, taxation or other policy measures (e.g., retroactive FiT change).
Price risk	The risk of price volatility within a stable policy regime (e.g., merchant price exposure under a feed-in premium policy).
Resource risk	The risk of lower revenues due to inaccurate resource potential estimation (e.g., wind speed or solar irradiation).
Technology risk	The risk of lower revenues or higher maintenance costs due to the technology's novelty and unpredictability (e.g., faster degradation).

specified), the technology (if specified), the time (if specified), the direction of change (increasing, constant or decreasing) and the risk dimension (impact or probability). The coding was done in English to ensure comparability. Fig. 3 shows the distribution of the 869 coded segments, while Figure A3 in the Appendix shows the number of assigned risk type, risk driver and direction of change codes for each interview. Note that several codes can be assigned to one segment.

For each statement, the coder then assigned a driver (if applicable). The coder developed these drivers iteratively to best fit the interview statements. In grounded theory, this procedure is termed "open coding" – the unconstrained comparison of incident (i.e., statement) to incident to generate categories (i.e., of drivers). This is an iterative process used to identify common patterns. Once the drivers were categorised, we used MaxQDA to analyse the links between risk types and drivers. Specifically, we counted co-occurrences of different code types (e.g., risk type and risk driver) and developed a network that illustrates connections across all coded interviews. This enabled us to identify the most relevant drivers for each risk type by using the 869 coded segments.

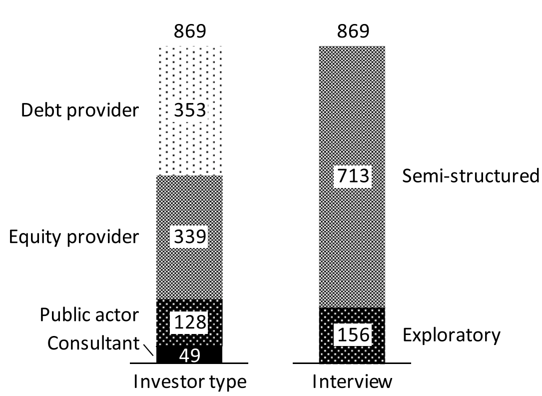

Fig. 3. Number of coded segments according to investor type (left) and interview type (right).

3. Results and discussion

In Section 3.1 of this paper, the evolution of risk premiums in Germany, Italy and the UK is discussed. Section 3.2 presents the most relevant risk types and shows the evolution of their importance over time. Section 3.3 identifies the drivers behind the changes and provides qualitative evidence to support the links between driver and risk type.

3.1. Changes in risk premiums

As shown in Egli et al. (2018), debt finance offers a clean way to operationalise project risk through debt margins. Debt providers typically charge a margin on top of a baseline rate for each credit they hand out. Because RET projects are usually financed in project finance structures in Germany, Italy and the UK, the risks associated with the credit are directly linked to the underlying project (Steffen, 2018). For riskier projects, investors typically demand higher debt margins as buffer. Fig. 4 averages the data for Germany from Egli et al. (2018) over the anchoring year and the previous year and adds data for Italy and the UK. It shows that project-specific debt margins decreased between 11% and 42% from 2008/09 to 2016/17, depending on the country and technology. In all three countries, the decline in debt margins was stronger for solar PV than for onshore wind. The debt margins of the two technologies were similar early on in Germany, while in Italy and the UK, the debt margins for onshore wind were lower than those for solar PV. In contrast to this overall decline, the debt margins in Italy remained roughly constant or increased from 2008/09 to 2012/13. This may be related to the looming concern about Italian policy credibility prior to the cut in large solar PV feed-in tariffs (FiT) in 2014 (*spalma incentivi*), which was ruled constitutional in 2017 (Steinhauer and Narducci, 2017).

The evolution of other financial indicators that reflect investment risk (cf. Egli et al., 2018) – such as loan tenor, leverage ratio and debt service coverage ratio (DSCR) – is explained in Table A4 in the Appendix. Longer loan tenors, increasing leverage ratios and decreasing DSCRs generally confirm the decrease in RET investment risk over time. The change towards less risky comparable asset classes to RET investments between 2009, 2013 and 2017 (see Figure A4 in the Appendix) confirms these trends. While a comparable asset class in 2009 was a corporate bond of an established and listed company, today it is a low-risk infrastructure investment. The overall decline of risk premiums and the technology difference in that decline (stronger in solar PV than onshore wind) are consistent with other findings for Germany. As experience (the technology's track record) and corresponding data availability are key drivers in reducing risk, the fast deployment of solar PV in the period under study contributed to this faster risk reduction. In fact, as one investor put it, solar PV has become a commodity: "So, you see a deeper decrease in [the] perception of risk [for solar PV] because it is already considered a commodity". Onshore wind, in contrast, is a more complex technology to operate; as another investor explained: "With onshore wind, you have more moving parts and if there is a fault with the gear box, for example, it is possible that you have to demount the entire nacelle, leading to long out-of-service periods. [With solar PV, in

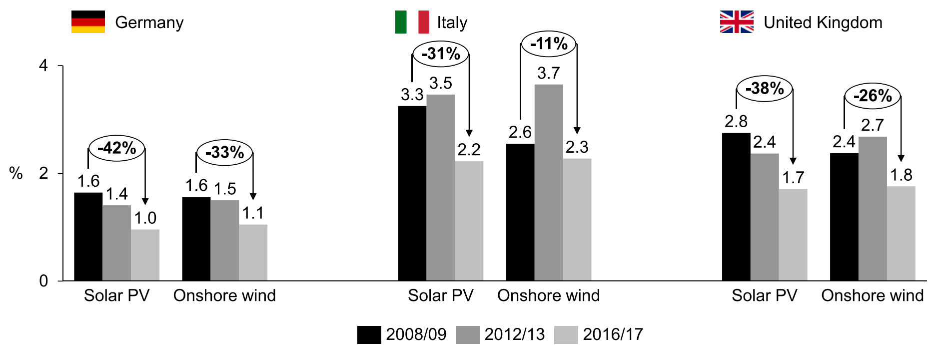

Fig. 4. RET debt margins by country and technology (N = 79).

contrast,] replacing one or two modules only leads to a row of modules not producing electricity".

In sum, risk premiums – measured with different indicators – and investment risk decreased substantially for solar PV and onshore wind in Germany, Italy and the UK between 2009 and 2017. This confirms and expands the findings of Egli et al. (2018) from Germany to Italy and the UK.

3.2. *Risk types and dynamics over time*

By screening the literature systematically to establish a long list of RET investment risks, we identified 22 relevant papers (see Table A3 in the Appendix for a full list of papers and risks). Based on the scope of the study and using the exploratory investor interviews, we defined the five RET investment risk types most relevant for investment decisions. Table 1 provides definitions of these five risk types, which were elaborated in the exploratory interviews. The interview transcripts confirm that all five risks were mentioned frequently, with policy risks mentioned most frequently and curtailment risks least frequently (see Figure A5 in the Appendix). Here, curtailment risk refers to uncompensated and unexpected (i.e., not ex ante predictable at the time of the investment decision) curtailment.

In this section, we report changes in the relative importance of these risk types. It is important to keep in mind that these are risk rankings and hence convey the *relative* importance of one risk type versus another. Fig. 5 shows changes in the relative importance of the five risk types between 2009 and 2017. Note that the figure includes risk assessments in which no country or technology was specified, as well as country– and technology–specific assessments. Overall, technology and policy risks declined the most, while price and curtailment risks increased the most and resource risk stayed approximately constant (all in relative terms). This pattern is confirmed when analysing the network data from the coded interviews. Figure A6 in the Appendix shows that curtailment and price risks were typically mentioned when the interviewee talked about risks increasing in importance. Policy, resource, technology and general RET investment risks were usually mentioned in statements about decreasing risks.

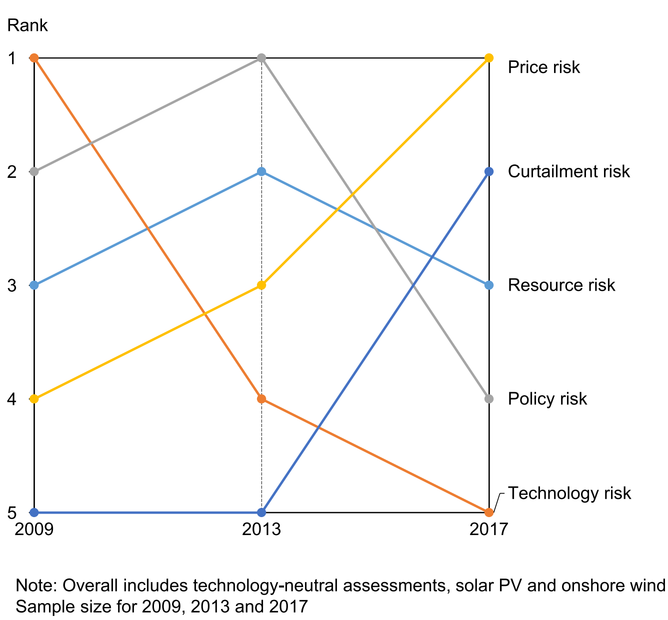

Fig. 5. Relative importance of risk types (1 = most important; 5 = least important). Sample sizes are N = 32 for 2009, N = 37 for 2013 and N = 38 for 2017.

While Fig. 5 shows aggregate changes, the interviews show that some risks vary by technology or country (policy context). To define which risk types vary based on which dimensions, we relied on the coded interviews. If interviewees mentioned a risk type together with a specific country (indicating a particularity of that risk type regarding the country), the evolution of the risk importance was charted by country (see Table 2). If interviewees mentioned a risk type together with a specific technology (indicating a particularity of that risk type regarding the technology), the evolution of the risk importance was charted by technology (see Table 3). Figure A7 in the Appendix shows that, in the coded interview statements, resource and technology risks co-occur with technologies, while policy and price risks co-occur with countries. Curtailment risk does not appear in Figure A7, because it is still a relatively recent phenomenon. However, we infer qualitatively from the interview statements that curtailment risk depends on country (e.g., grid structure, RET share, remuneration policy) rather than technology. Tables 2 and 3 show the relative ranks of country- and technology-specific risk types for 2009, 2013 and 2017. The arrows indicate the direction of change over time. We focus the discussion on the direction of change and the relative importance of risk types (high – low) because sample sizes for Tables 2 and 3 are considerably smaller than in Fig. 5, likely making the displayed rankings less robust.

Table 2 shows that investors ranked curtailment risk low in most years. However, this risk increased in importance over time in Germany, where RET shares of electricity generation are highest. The relative importance of policy risk differs substantially between countries. In Germany investors ranked this risk second in 2009 and 2013, but it had become the least important risk type by 2017. In Italy, in contrast, the

Table 2
Risk ranks and changes in relative importance for country-specific risk types. Sample sizes are N = 10 for Germany, N = 4–7 for Italy and N = 1 for the UK.

	Germany	Italy	UK
	2009 | 2013 | 2017	2009 | 2013 | 2017	2009 | 2013 | 2017
Curtailment risk	5th ↗ 4th ↗ 3rd	4th ↘ 5th ↗ 4th	5th → 5th → 5th
Policy risk	2nd → 2nd ↘ 5th	5th ↗ 1st ↘ 2nd	1st → 1st ↘ 2nd
Price risk	1st ↘ 3rd ↗ 2nd	3rd ↗ 2nd ↗ 1st	4th → 4th ↗ 1st

Table 3
Risk ranks and changes in relative importance for technology-specific risk types. Sample sizes are N = 12–14 for solar PV and N = 11–13 for onshore wind.

	Solar PV	Onshore wind
	2009 | 2013 | 2017	2009 | 2013 | 2017
Resource risk	4th ↗ 3rd ↘ 4th	1st → 1st ↘ 2nd
Technology risk	3rd ↘ 4th ↘ 5th	4th → 4th → 4th

relative importance of policy risk skyrocketed in 2013 and decreased only slightly from 2013 to 2017. In the UK, policy risk was ranked high throughout the entire time period. Meanwhile, investors identified an opposite trend in price risk, with relative increases in all countries between 2013 and 2017 (no trend between 2009 and 2013).[9]

Technology-specific risk types are shown in Table 3. Investors ranked resource risk consistently high for onshore wind and low for solar PV – even as early as 2009. They ranked technology risk for solar PV lower over time, reflecting users' increasing experience with solar PV and the maturing of the technology. In 2017 technology risk was the least important risk type for solar PV, reflecting its modularity, which makes it less prone to technical failures on a system or plant level. In the case of onshore wind, investors ranked technology risk low from 2009 through 2017, indicating that the technology was already relatively mature and proven even in 2009. Due to its higher complexity than solar PV (see Section 3.1), there was, however, no decrease in the relative importance of technology risk for onshore wind over time.

3.3. *Drivers of change*

In the final step, we used evidence from the coded interviews to link drivers to the observed changes in importance of risk types. This section discusses each risk type and its most important drivers, providing one or more representative quotes from the interviews for each. Fig. 6 shows the connection between risk types and driver categories based on coded co-occurrences in the interviews. Note that several drivers can be linked to one risk type in one interview statement. Hence, the count does not represent the number of coded statements, but the number of co-occurrences (for the number of coded interview statements by risk type, see Figure A5).

Curtailment risk became relatively more important overall between 2009 and 2017 – a development mainly driven by Germany (see Table 2) – because the risk starts to materialise only at high levels of RET penetration. In Germany, for example, curtailment sharply increased with the expansion of RET generation (Schermeyer et al., 2018). As one investor explained, Germany experiences (at times) unexpected curtailment: "I have seen it with wind in Germany and really the trend there is as you have got more energy coming in at a given time, then you are finding that the grid operator is going to shut you down". The main driver of curtailment risk is policy credibility and setup (see Fig. 6), which determines, for example, whether RET generation can be fed into the grid with priority over other sources and whether curtailment (e.g., due to grid constraints) will be compensated by the policymaker. In Germany, since 2014, RET production must be sold at a zero subsidy if electricity prices are negative during six consecutive hours. In 2017 curtailment risk became a relevant factor to consider in investment proposals as a consequence (Linkenhell Perez and Küchle, 2017). In markets with less developed grids, curtailment becomes a factor at low but concentrated levels of RET penetration. However, for Germany, Italy and the UK, this is not an issue.

Policy risk was one of the most important risks in 2009 and 2013 and declined substantially in relative importance between 2013 and 2017 (see Fig. 5). Developments in Germany, where policy risk declined rapidly relative to the other risks after 2013, largely drove this overall effect. In Italy, in contrast, policy risk became the most important risk in 2013 and remained relatively important in 2017. As mentioned previously, this is mainly due to the retroactive FiT changes implemented in Italy. Several investors brought up this point in the interviews. As one of them put it, "There were some legislative actions, that were perceived very critically by the market [participants]". Another investor said, "With *spalma incentivi*, they enacted a reversal that was implemented more or less market compatible and with a sense of proportion by the lawmakers". In the UK, policy risk was constantly ranked high, which may be a result of frequent policy changes and the inconsistency of the UK's energy policy in a market-based and interventionist regime (cf. Keay, 2016). These changes in policy risk stem from three drivers: policy credibility and setup, technology characteristics and developments, and data availability and assessment tools (see Fig. 6).

The credibility of policies and their future trajectory is a main reason that policy risk decreased in Germany relative to the other risks and increased in Italy. However, other factors also contributed. For example, investors understood policymakers better over time, so future policy adjustments became more predictable, thereby decreasing the policy risk. As one investor put it: "There is regulatory learning. You understand the regulator better, and you know what they are thinking". This exchange of knowledge between investors and regulators may also have contributed to the design of the retroactive policy change in Italy that spared investors (mainly on the debt side) from large negative impacts. However, some investors believe this was rather the result of the political power of heavily invested Italian banks than the result of an intentionally well designed policy due to efficient knowledge exchanges between investors and regulators. Another factor contributing to the first driver is concern about policy costs being perceived as too high by the public. One investor explained: "The financial returns on the projects were absolutely crazy because the costs were falling so fast… and the policymakers just could not keep up. Actually, I do not even know if the policymakers realised how generous they were being". This factor potentially increases the risk for retroactive policy change as policymakers are pressured by the public to lower policy costs.

To some extent, the second driver – technology characteristics and developments – has softened this concern. Rapidly decreasing technology costs have lowered the impact of potential policy changes as generation costs approached market prices. Many statements confirm this either directly or indirectly via power purchasing agreements (PPA) with the government gaining in credibility due to lower cost. One investor explained, "The risk decreased because of a lower delta between subsidies and market price". Another confirmed, "The risk is decreasing the closer we get to competitiveness and market prices". Both of these statements reflect a relative decrease in investment risk as the gap between subsidy price and market price narrows. In other words, investors are becoming less dependent on RET support policies as their outside options (such as selling electricity on the wholesale market) become more attractive. This is a direct effect of decreasing technology costs, to which subsidies respond. An additional indirect effect of decreasing technology costs is the increase in credibility of RET support policies as their cost decreases. As another investor described, "The closer we are to market prices, the higher the probability that the [PPA] contracts are fulfilled".

The third driver relates to difficulties in assessing wind resources, as more wind parks are being built and dedicated land area slowly fills up. In reaction, policymakers enact zoning changes, which extend the area where RET plants can be built. For onshore wind, an unexpected consequence is that wind turbines are often built in proximity to existing

[9] Note that the high ranking of price risk in Germany in 2009 was driven by one investor, who ranked price risk first for both onshore wind and solar PV. The investor's assessment was based on inflation risks in a nominal FiT and unrelated to the risk of exposure to merchant risk. "I looked at many inflation risks, because we thought that [the economic crisis] would lead to money being pumped into markets and the public sector, [which would lead] to inflation risks in the medium term [because] the FiT was fixed in nominal terms", said the investor.

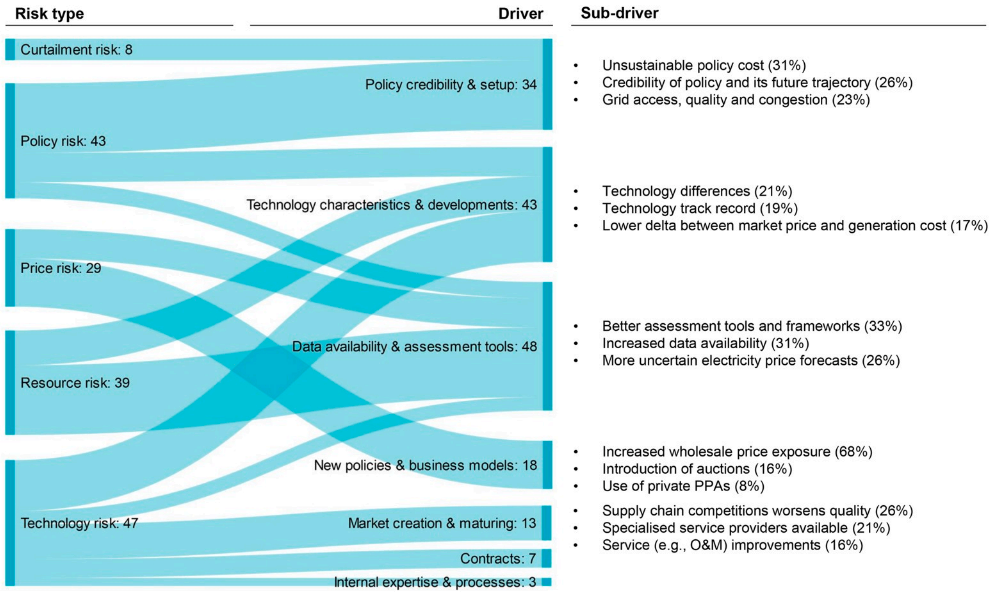

Fig. 6. Risk types and corresponding drivers. Links with fewer than three co-occurrences are omitted. The width of the link is proportional to the frequency of co-occurrence. Most frequent sub-drivers are indicated for drivers with more than 10 co-occurrences.

turbines, which causes wind turbulence and decreasing yield due to spatial interference. One investor explained the issue for Germany: "Nobody can guarantee you that the zoning does not change next door. ... In 2016, our in-house lawyer spent most of his time suing wind parks that were built in proximity. ... [Spatial interference from nearby wind parks] can lead to a 20–30% loss of production".

Price risk is the only risk that increased in relative importance from 2009 to 2013 and from 2013 to 2017 (see Fig. 5). It was always relatively important in Germany due to potential inflation risks, and it has become more important in Italy and the UK over time (see Table 2). New policies and business models were the most important drivers of price risk and influenced another driver of price risk – data availability and assessment tools.

The move towards more market-based RET policies, including wholesale price exposure or premium auctions, is the main driver of price risk. For an investor, these policies introduce volatility in future cash flows and, therefore, increase risk margins (cf. Pahle and Schweizerhof, 2016). Since 2017, auctions have increasingly produced subsidy-free (i.e., zero premium) contracts in European countries for onshore wind and solar PV (Wronski, 2018). The introduction of price risk via auctions was noted as a risk driver by several investors. For example, one said: "Price risk is becoming more important. As we are in a bidding system, we have to take into account market prices more often". Another investor explained that securing financing potentially becomes more difficult in an auction system: "As you go into an auction as a developer, you need to present the sealed financing deal already. ... For banks, this is a tricky game because of the many assumptions in the financing deal. For example, if the plant needs to be built within two years after winning the bid, [the bank] needs to estimate future technology and operating costs etc.". However, the risk initiated by auctions may also be temporary. In Germany an investor noted that the industry learns quickly and adapts to new policies: "For solar PV, we have seen auctions for a bit longer and hence everything is already a bit more settled and in order after the little storm that we saw".

Due to increasing exposure to market prices, the profitability of RETs depends on future electricity prices. Assessment tools become less accurate due to this fundamental uncertainty, as one investor explained, "Because you calculate project [revenues] over a long time, while you fully look into a black box regarding the future price [of electricity]". For example, the speed of electric vehicle deployment will have a major impact on future electricity prices. Another investor claimed that there is "just a lot of uncertainty on how these markets will develop in terms of electric vehicles coming on the grid... and whether storage will be there or not". The shift to more market-based RET policies also creates an incentive to use private PPAs. This potentially increases risk because it exposes the investor to the business risk of the private counterparty and hence requires an additional examination of the counterparty's creditworthiness. As one investor put it, "In a [private] PPA, I am actually in corporate finance again".

Resource risk stayed approximately constant in relative importance between 2009 and 2017 (see Fig. 5). It was of consistently high relative importance for onshore wind, and low relative importance for solar PV (see Table 2). The two main drivers of resource risk are technology characteristics (differences) and developments (new designs), and improved assessment tools due to increasing data availability.

Wind predictions are less precise than solar irradiation predictions, which makes resource risk more relevant for onshore wind. One investor explained: "Our solar PV portfolio is absolutely stable... However, with wind resources, there is always an uncertainty that does not exist with solar irradiation, which is very stable, calculable and predictable". The emergence of new wind turbine designs (higher masts) and complications in estimating wind speeds with other turbines close by (spatial interference) are also causing new problems for wind predictions. Installed onshore wind turbines have been growing consistently in capacity, rotor diameter and hub height (Fraunhofer IWES; Greentechmedia, 2018), which has also introduced new difficulties for resource estimation. As one investor noted, "I know a bit better how the wind blows 100 m above ground, but this does not tell me the wind speed 160 m above ground".

However, at the same time, data on wind speeds (from existing turbines), including detailed spatial resolution, have become increasingly available. Subsequently, assessment tools and wind resource models have improved, leading to a drastic decline in resource risk. Typically, models are now able to estimate returns over a longer time and uncertainty has thus been narrowed (e.g., the difference between the often-used 90th percentile and the median has narrowed). One investor explained the decrease in risk: "[The] assessments became more accurate... Hence, because the capital structure is mainly driven by resource uncertainty, there is clearly more debt available today compared to 2009".

Technology risk experienced the most pronounced change in relative importance between 2009 and 2017 (see Fig. 5). While it was the most important risk in 2009, it had become the least important by 2017, with most of the change occurring between 2009 and 2013. This change occurred mainly in solar PV (see Table 3), and it is linked to five drivers.

Technology characteristics and developments are the most important driver of technology risk. A successful technology track record (including data availability) is the main prerequisite for a lower technology risk. As one investor explained: “We just saw that the first parks going into operation in Germany around 2005 and 2006 ran consistently without problems for around eight years”. Such positive experiences lead to spillovers across the industry. An investor noted: “A lack of experience leads to a certain reservation. The broader the phenomenon of renewable energies, the more cases you have and the more exchange [of experiences] happens across all levels (e.g., board members, conferences)”.

However, for onshore wind, new turbine designs have also led to an increase in technology risk. Not only have resource estimations become more difficult as hub heights have increased, but unknown wind speeds and turbulences have also created technology risk (e.g., damages or interrupted generation). One investor explained: “We hesitate to finance new turbine types. At least, we require guarantees from the supplier that go beyond those we require for turbines with extensive operational experience”. Overall, the increase in technology risk from new technology designs remains marginal compared to the decrease in technology risk brought about by a technology’s successful track record.

The second-most important risk driver is market creation and maturing. A more mature market attracts new service providers and leads to service improvements, which lower technology risk (e.g., more efficient cleaning operations for solar PV, better operation and maintenance (O&M) contracts or cheaper O&M). For example, solar PV plants started using string inverters (decentral) instead of central inverters to reduce O&M risks. As one investor explained: “Besides the modules, the inverters are the second-most important topic... To fix a central inverter, you need highly qualified staff. If you are in Sicily and need to wait for them to fly in from Germany, you may lose an entire day”. However, as the market matures, competition also increases in the supply chain, which can lead to quality issues. For example, wind turbine manufacturers were under strong pressure during a phase of rapid deployment in Germany, which led to manufacturing mistakes (such as using the wrong glues), lowering the quality of the turbines in French wind parks.

The third driver concerns the extension of contract scope and the standardisation of contracts. RET contracts have shifted from a performance guarantee (i.e., hours per year) to a production guarantee (i.e., megawatt hours per year), eliminating the risk of losses due to resource-poor times. One investor described this trend: “Meanwhile, producers moved to provide availability guarantees”. Similarly, contracts have started to include clauses to safeguard against uncompensated curtailment and are being drafted in a standardised way.

The fourth driver, more reliable assessment tools, also reduced technology risks, as more performance data became available (see the section on resource risk for a description and quotations from investors). Finally, the fifth driver, internal capabilities, has resulted in lowered technology risk. As investors typically did not have experience with RET projects in the early years, they assembled skilled teams with the capability to assess the technological risks of onshore wind and solar PV. In turn, risk assessments became more precise and risk margins decreased. As one investor explained: “We hear from many investors that processes were streamlined, became faster, cheaper and more standardised”.

Further risk types, which are not specific to RETs but affect RET investment risk nonetheless, were also mentioned in the investor interviews. For example, the expansionary monetary policy in Europe has led to excess liquidity in the market, increasing competition for RET projects and hence lowering returns and risk margins. As one investor explained: “Changes in the markets due to the macroeconomic environment and the financial markets increased liquidity. Correspondingly, we see a strong yield compression, which leads to lower returns”. Additionally, the maturing investment ecosystem – together with more experienced investors – has created trusted relationships to facilitate RET investments. Investors like to do business with known partners. An investor explained, “That is our principle: whenever possible, we like ‘serial offenders’ [because] we can build on [an existing relationship]”. An investor noted that learning has happened on all levels to help bring technology costs down: “The developers learn a lot. The financial investors learn over time, and the regulators, too, learn over time. That total learning effect leads to decreasing levelised costs of electricity”.

4. Conclusions and policy implications

This paper makes four contributions to the field: First, we show that solar PV and onshore wind financing conditions improved in Germany, Italy and the UK between 2009 and 2017; this improvement was accompanied by lower risk assessments from investors. Second, we identify curtailment, policy (reversal), price, resource and technology risks as the five most important RET investment risk types. Third, we demonstrate that policy and technology risks became relatively less important over time, while curtailment and price risks became relatively more important (while resource risk stayed approximately constant). Resource and technology risks depended on the technology type, while curtailment, price and policy risks depended on the country (i.e., policy). Fourth, we identify the main drivers responsible for the changes in the importance of each risk type.

These findings allow us to put forth a stylised revenue model for RET investment risk. Technology-specific risk types impact the generation output (Q), whereas country-specific risk types impact the obtained price (P) or the ability to feed the produced electricity into the grid and therefore sell the production (γ). Equation (1) shows the three components of revenue (R); equation (2) gives the expected project revenues (*E(R)*); equation (3) indicates the bounds for two of the variables.

$$R_{(€)} = Q_{(MWh)} \times P_{(€/MWh)} \times \gamma \tag{1}$$

$$E(R) = [\overline{Q} \times \alpha \times \beta] \times [\delta \times E(P) + (1 - \delta) \times \overline{P}] \times \gamma \tag{2}$$

$$\gamma, \delta = [0, 1] \tag{3}$$

Equation (2) shows that the realised electricity output depends on the electricity generation capacity ($\overline{Q}$) and two parameters: the first (α) describes the deviation from the generation capacity due to technical failure; the second (β) describes the deviation from expected resource potential due to actual resource availability. Taken together, the first part of equation (2) describes expected electricity generation.

The second part of equation (2) depicts the expected price per megawatt hour for a simplified case in which a RET plant either operates in a FiT regime or sells electricity in a merchant market. The expected price depends on a fixed remuneration level ($\overline{P}$; e.g., FiT), the probability (δ) that this remuneration level is changed retroactively and the expected wholesale electricity price (*E(P)*) that the generation would be remunerated for in this case. In practice, a retroactive policy change may also be an increase in the tax rate or other RET-specific regulation that increases the cost of generation, as happened in Spain in 2015 for solar PV (Daley, 2014; Tsagas, 2015). The level of remuneration after a policy change may still be higher than *E(P)*. Lastly, the curtailment factor (γ) represents the expected share of the generation that can be fed into the grid.

Both researchers and policymakers can use equation (2) as an analytical lens through which to look at RET investments. Researchers can then try to integrate risk metrics into models that use endogenous investment into RETs. For example, some of the presented risk metrics – such as debt margins or DSCRs – can serve as proxies for certain risk types. Integrating such dynamics into RET deployment models may serve to make them more realistic and to make trade-offs in policy designs visible (Egli et al., 2019). More research is needed to develop the mechanism through which the importance of different risk types changes and determine the precise impact that policy designs have on the risk types. Our research points to an important time lag between technical readiness and access to low-cost financing for a technology. As one investor put it, "The flip between emerging and mature [technologies] is not down to technology readiness level; it is down to commercial readiness level". How technologies transition from technical to commercial readiness, and how this transition may be accelerated using smart policies to increase knowledge spillovers between investors and create a resilient RET investment ecosystem (e.g., trusted partners with a common understanding of risks), is an interesting avenue for future research. In this regard, it is particularly interesting to look at early investment risks, such as planning and construction risks, as these risks are likely to be more relevant for less mature low-carbon technologies, which may be needed to reach the goals of the Paris Agreement.

For policymakers, this research offers insights into the potential for accelerating RET deployment by reducing investment risk and thus RET financing costs. First, our results indicate that retroactive policy changes are costlier in early technology phases when the generation costs differ significantly from market prices. This has implications for policy credibility and stability, which is more important in the early phases of technology development. For latecomers this may mean that frequent policy changes in the past do not necessarily deter future investment. Second, our results point to the importance of sharing data and expertise in order to develop credible and accurate financial and technical models. RET lighthouse projects (large projects using new technology in cooperation with strategic partners) may, therefore, be crucial in establishing confidence in RET markets to bring down financing costs. However, the usefulness of such projects depends on their openness to sharing all data (financial and technical). Third, exposing RET projects to market risks may threaten RET investment, although RETs have reached cost competitiveness with FFTs. Importantly, risk should be phased in gradually in view of the general macroeconomic and interest rate environment (Schmidt et al., 2019) and the success of such a phase-in may depend on the existence of a mature investment ecosystem. Only if such an ecosystem is present can the actors develop the products and structures to distribute and manage risk effectively with the technical knowledge required to assess the affected RETs.

Declaration of competing interest

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

CRediT authorship contribution statement

Florian Egli: Conceptualization, Data curation, Formal analysis, Writing - review & editing.

Acknowledgements

The author thanks B. Steffen, T.S. Schmidt and other members of ETH's Energy Politics Group and O. Tietjen from the INNOPATHS project for helpful comments on earlier drafts of the paper. Further thanks goes to participants of the 1st Energy Innovation Academy in 2018 at the Florence School of Regulation, European University Institute, the 7th International Symposium on Environment and Energy Finance Issues in 2019 in Paris and the 16th IAEE European Conference in 2019 in Ljubljana. This work was supported by the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract number 16.0222. The opinions expressed and arguments employed herein do not necessarily reflect the official views of the Swiss Government. This work was conducted as part of the European Union's Horizon 2020 research and innovation programme project INNOPATHS under grant agreement no. 730403 and the Competence Center for Research in Energy, Society and Transition (CREST), supported by Innosuisse – the Swiss Innovation Agency.

Appendix A

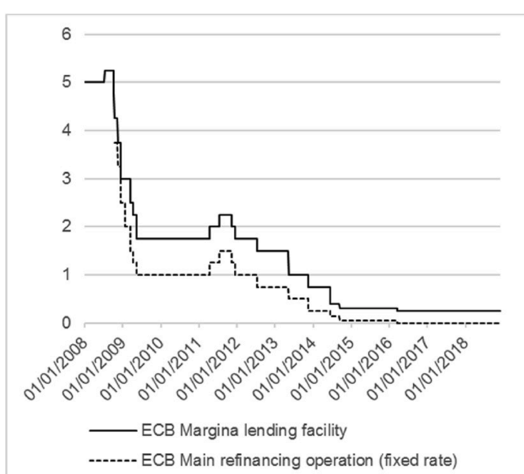

Fig. A1. ECB interest rates

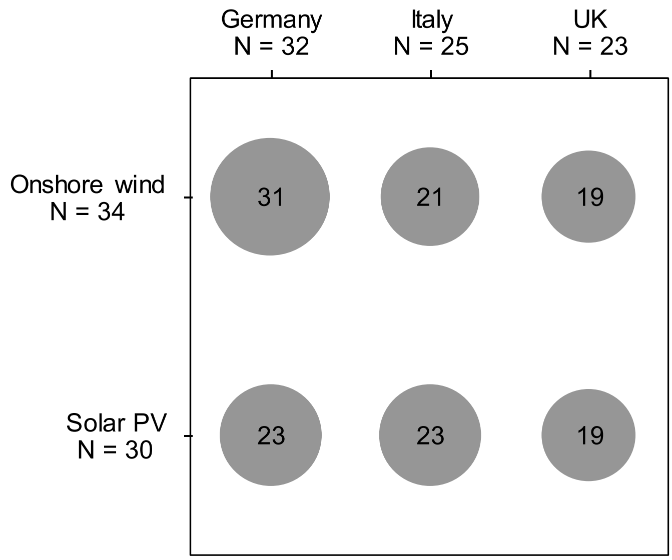

Fig. A2. RET investment experience across countries and technologies for the sample of interviewed investors.

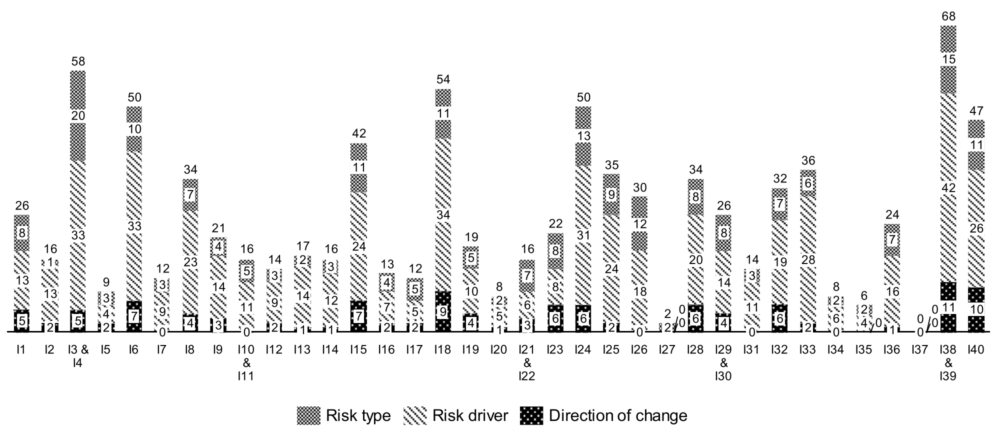

Fig. A3. Number of assigned risk type, risk driver and direction of change codes for each interview.

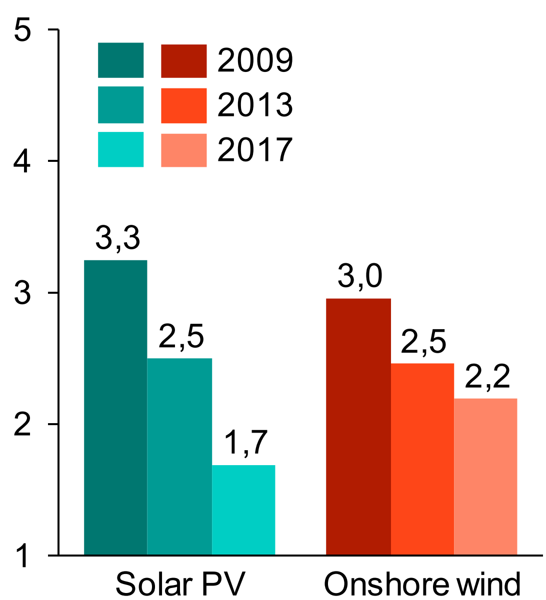

Fig. A4. Overall RET investment risk by technology by selecting a comparable asset class for 2009 (N = 7), 2013 (N = 9) and 2017 (N = 10). 1 = 10-year government bond, 2 = low-risk infrastructure investment, 3 = corporate bond of an established and listed company, 4 = stock of a listed company, 5 = early stage venture capital investment.

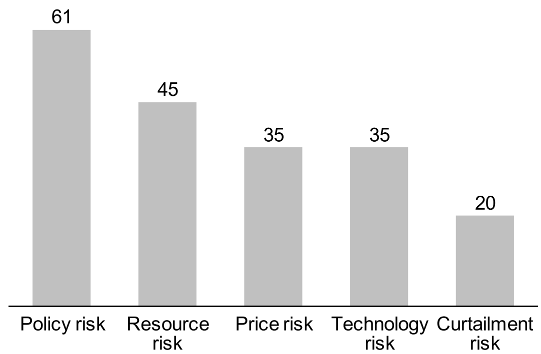

Fig. A5. Risk type code frequency where indicated counts refer to the number of coded interview statements that were assigned a given policy risk type.

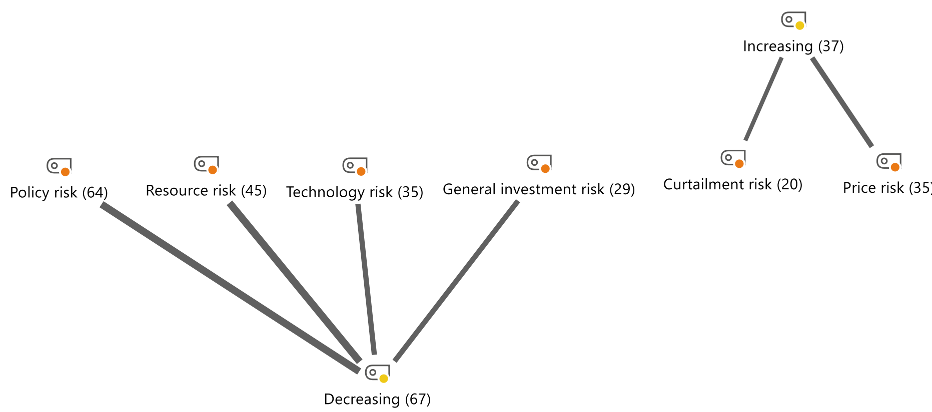

Fig. A6. Risk types and direction of change. Co-occurrence of codes in coded segments across all investor interviews. Width of connection indicates frequency, total number of assigned codes in brackets. Figure shows only codes with at least five co-occurrences.

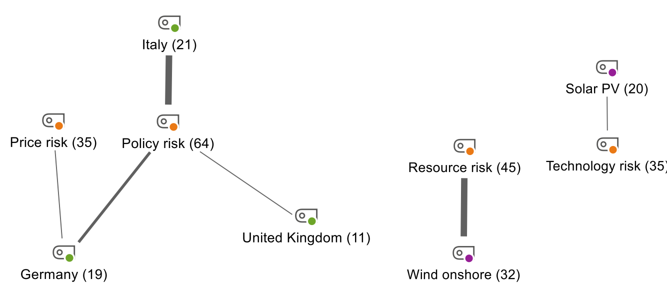

Fig. A7. Country- (left) and technology-specific (right) risk types. Co-occurrence of codes in coded segments across all investor interviews. Width of connection indicates frequency, total number of assigned codes in brackets. Figure shows only codes with at least five co-occurrences.

Table A1
Interview questions.

Q1	What year did you start working in renewable energy investment?
Q2	In which countries and technologies do you have investment experience? *[Solar PV and onshore wind in Germany, Italy and the UK to choose from]*
Q3	How risky did you perceive an investment in renewable power (solar PV, wind onshore) from 1 (not risky at all) to 5 (very risky)? *[Solar PV and onshore wind in 2009, 2013 and 2017]* *[Legend:* *1 –The risk is comparable to a 10 year government bond* *2 –The risk is comparable to a low-risk infrastructure investment* *3 –The risk is comparable to a corporate bond of an established and listed company* *4 –The risk is comparable to a stock of a listed company* *5 –The risk is comparable to an early stage VC investment]*
Q4	Please rank the risks from most (1) to least (5) relevant using each number only once for general renewable energy investment from the list below. *[Five risk types in 2009, 2013 and 2017; possibility to indicate country- or technology-specificity]*
Q5	Which risks have changed most? Are there differences across risks, technologies and countries?
Q6	What are the main drivers behind the changes? Are these drivers company specific, country specific, or global?
Q7	Could you describe the processes, how risks change over time, which actors are involved, how synergies may play a role, etc …

Note that Q5, Q6 and Q7 were deliberately open questions, which led into the qualitative part of understanding risk drivers.

Table A2
List of interviewees

ID	Interview type	Current organisation	Current position	Based in	RET investment experience (years)
1	Structured	Debt provider	Head of Division Energy & Utilities	Germany	12
2	Structured	Debt provider	Vice President	Germany	28
3	Structured	Debt provider	Associate Director Project Finance & Capital Advisory	Germany	7
4	Structured	Debt provider	Associate Director Infrastructure & Power Project Finance	Germany	9
5	Structured	Debt provider	Executive Director Project Finance Renewable Energies	Germany	21
6	Structured	Debt provider	Associate Director Global Infrastructure Debt	United Kingdom	5
7	Structured	Debt provider	Head Renewable Energies	Germany	27
8	Structured	Debt provider	Project Finance Analyst	Germany	11
9	Structured	Debt provider	Vice President Corporates & Small Business Project Finance	Germany	11
10	Structured	Debt provider	Director Structured Finance Power & Renewables	The Netherlands	11
11	Structured	Debt provider	Director Structured Finance Utilities, Power & Renewables	The Netherlands	11
12	Structured	Debt provider	Senior Manager Structured Finance Renewable Energy	Germany	19
13	Structured	Debt provider	Director Project & Structured Finance Utilities, Power and Renewables	Italy	11
14	Structured	Debt provider	Director Corporate Strategy	The Netherlands	19
15	Structured	Debt provider	Head of Renewable Energies	Germany	23
16	Structured	Debt provider	Head of Project Finance Origination Renewable Energies	Germany	8
17	Structured	Debt provider	Managing Director Project & Acquisition Finance	United Kingdom	12
18	Structured	Equity provider*	Head Risk Advisory	Germany	13
19	Structured	Equity provider*	CEO	Germany	10
20	Structured	Equity provider*	Founder and CEO	Germany	5
21	Structured	Equity provider	Principal	Switzerland	5
22	Structured	Equity provider	Partner	Switzerland	9
23	Structured	Equity provider	Director Infrastructure Equity Investment Team	Germany	12
24	Structured	Equity provider	Vice President Renewables	Switzerland	3
25	Structured	Equity provider	CIO	Germany	2
26	Structured	Equity provider	CEO	Germany	2
27	Structured	Equity provider	Associate Director Energy & Cleantech	France	12
28	Structured	Equity provider	Associate	United Kingdom	18
29	Structured	Public actor	Head Energy Services	Switzerland	12
30	Structured	Public actor	Deputy Head Energy Management	Switzerland	3
31	Structured	Public actor	CEO	Switzerland	7
32	Structured	Public actor	Head Portfolio and Asset Management Renewable Energies	Switzerland	8
33	Structured	Public actor	Vice President Origination and Structuring	Germany	6
34	Structured	Equity provider	Investments Director	United Kingdom	12
35	Structured	Public actor	Senior Investment Manager	Norway	11
36	Structured	Public actor	Economist	Luxemburg	15
37	Exploratory	Equity provider*	Head Risk Advisory	Germany	13
38	Exploratory	Equity provider	Partner	Switzerland	9
39	Exploratory	Equity provider	Principal	Switzerland	5
40	Exploratory	Other (consultant)	Head Hybrid Power Solutions	Germany	12

Table A3
RET risk types from the literature

Source	Risk types
Breitschopf and Pudlik (2013)	• Technology risks • Performance risks • Policy risks • Market risks • Resource risks
Gatzert and Kosub (2016)	• Strategic/business risks • Transport/construction/completion risks • Operation/maintenance risks • Liability/legal risks • Market/sales risks • Counterparty risks • Political, policy, regulatory risks
Frisari et al. (2013)	• Political, policy, social risks • Technical, physical risks • Market, commercial risks • Outcome risks
Steggals et al. (2017)	• Development risks • Construction risks • Operating risks • Resource risks • Curtailment risks • Price & offtake risks • Policy risks • Political risks • Currency risks
(Angelopoulos et al., 2017, 2016; Ecofys, 2016)	• Country risk • Social acceptance risk • Administrative risk

(continued on next page)

Table A3 (*continued*)

Source	Risk types
Waissbein et al. (2013)	• Financing risk • Technical & management risk • Grid access risk • Sudden policy change risk • Power market risk • Permits risk • Social acceptance risk • Resource & technology risk • Grid/transmission risk • Counterparty risk • Financial sector risk • Political risk • Currency/macro-economic risk
Dinica (2006)	• Contract risks (i.e. demand risks in general) • Price risks
Enzensberger et al. (2003)	• Technical risks (construction, technology) • Commercial risks (operation, market, financial) • Other risks (country, regulatory, social acceptance, force majeure)
Szabó et al. (2010)	• Technology risk • Market risk • Regulatoy policy risk • Geopolitical risk • Stakeholder acceptance risk
Economist Intelligence Unit (2011)	• Financial risk (access to capital) • Business/strategic risk • Building and testing risk • Operational risk • Environmental risk • Political/regulatory risk • Market risk • Weather-related volume risk (i.e. resource risk) • Other risk
Mitchell et al. (2006)	• Price risk • Volume risk • Balancing risk
Bouhal et al. (2018)	• Investment risk • Resource risk • O&M risk • Inflation risk
Neto et al. (2018)	• Resource risk • Price risk
Betz et al. (2016)	• Resource risk • Technology performance risk (incl. degradation) • Price risk
Kayser (2016)	• Technology risk • Market and financial risk • Policy risk
Lei et al. (2018)	• Construction risk • O&M risk • Policy risk • Technology risk
Salvo et al. (2017)	• Resource risk • Technology risk • Financial risk • Policy risk • Theft and natural disaster risk • O&M risk
Surana and Anadon (2015)	• Resource risk • Technology risk • Financing availability risk • Project implementation (incl. planning, construction, O&M) risk • Grid & transmission risk • Counterparty risk • Power market (incl. price and policy) risk
Justice (2009)	• Country and financial risks • Policy and regulatory risks • Technical and project-specific risks (incl. construction, performance, environmental, O&M) • Market risk (i.e., price risk)
Xingang et al. (2012)	• Competitive risk (e.g., market entry barriers) • Policy risk • Technology risk
Komendantova et al. (2011)	• Regulatory risk • Political risk • Revenue risk • Technical risk • Force majeure

(*continued on next page*)

Table A3 (*continued*)

Source	Risk types
Gross et al. (2010)	• Financial risk • Construction risk • Operating risk • Environmental risk • Price risks • Technical risks (incl. O&M) • Financial risks

Table A4
Other financial indicators.

Country	Technology	Period	CoC (%)	Debt margin (%)	Leverage (%)	Loan tenor (years)	DSCR	Bond yield (%)
DE	Solar PV	2008/09	4.7	1.6	80.0	15.8	1.18	3.6
DE	Solar PV	2012/13	3.2	1.4	81.7	17.2	1.18	1.5
DE	Solar PV	2016/17	1.4	1.0	87.5	18.6	1.13	0.2
DE	Onshore wind	2008/09	6.1	1.6	76.9	15.8	1.20	3.6
DE	Onshore wind	2012/13	3.2	1.5	75.1	17.0	1.17	1.5
DE	Onshore wind	2016/17	2.3	1.0	80.0	16.9	1.15	0.2
IT	Solar PV	2008/09	8.1	3.3	75.0	13.5	N/A	4.5
IT	Solar PV	2012/13	7.1	3.5	75.0	15.7	1.35	4.9
IT	Solar PV	2016/17	4.6	2.2	79.4	15.5	1.19	1.8
IT	Onshore wind	2008/09	8.9	2.5	75.5	13.5	1.40	4.5
IT	Onshore wind	2012/13	7.8	3.7	77.5	14.5	1.28	4.9
IT	Onshore wind	2016/17	4.3	2.3	82.0	18.0	1.21	1.8
UK	Solar PV	2008/09	6.5	2.8	75.0	15.5	1.40	3.9
UK	Solar PV	2012/13	5.0	2.4	72.2	13.5	1.49	1.9
UK	Solar PV	2016/17	3.0	1.7	77.5	17.5	1.33	1.2
UK	Onshore wind	2008/09	N/A	2.4	77.5	15.5	1.45	3.9
UK	Onshore wind	2012/13	4.8	2.7	75.0	13.6	1.54	1.9
UK	Onshore wind	2016/17	3.5	1.8	72.5	17.5	1.35	1.2

Note: For riskier projects, investors would typically decrease leverage (i.e. the amount of debt in a project) in order to safeguard against potential project losses that are borne by equity first and decrease loan tenors in order to reduce the risk exposure to a shorter period. The debt service coverage ratio (DSCR) is a measure of project cash flows available to pay debt obligations, namely the principal repayment and interest rate payments. Lower DSCRs can thus be interpreted as an indication for lower project risk.

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Paper 5

Bias in energy system models with uniform cost of capital assumption

Citation: Egli, F., Steffen, B., & Schmidt, T. S. (2019). Bias in energy system models with uniform cost of capital assumption. *Nature Communications*, *10*(1), 4588. https://doi.org/10.1038/s41467-019-12468-z

Contributions: F.E., B.S. and T.S.S. conceived the idea. F.E. carried out the analysis. F.E., B.S. and T.S.S. wrote the paper.

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Abstract

Several studies use energy system models to verify the feasibility of 100% renewable energy (RE) systems in the future. Some of these studies take into account regional, sub-regional or country-level variation in input data and display results on these levels too. Here, we argue that studies, which show country-level results, should abstain from using uniform or quasi-uniform costs of capital, because the resulting policy implications may be biased. Specifically, we argue that models using uniform costs of capital typically underestimate the cost of RE in developing countries and overestimate their cost in industrialised countries. On the one hand, these results may conceal important benefits of de-risking policies. On the other hand, they risk undermining policymakers' efforts to push for RE deployment in industrialised countries.

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https://doi.org/10.1038/s41467-019-12468-z OPEN

Bias in energy system models with uniform cost of capital assumption

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ARISING FROM D. Bogdanov et al. *Nature Communications* https://doi.org/10.1038/s41467-019-08855-1 (2019).

Several studies have recently evaluated the feasibility of 100% renewable energy-based energy systems in different world regions. In a recent article, Bogdanov et al.[1] contribute to this literature, by using an energy system model that takes into account the unique conditions of 145 global subregions, including factors such as renewable energy (RE) resource conditions, structure and age of existing capacities, demand patterns, etc. Based on their results, they discuss transition pathways and calculate the 2050 levelized cost of electricity generation (LCOE) of 100% RE-based energy systems in those 145 subregions. While the paper provides a new high-resolution analysis of 100% RE systems, we believe that it falls short of adequately considering large differences in the cost of capital (CoC) when comparing the LCOE between countries. As a result, Fig. 2 in Bogdanov et al. shows the lowest LCOEs for solar photovoltaic (PV)-based systems in countries such as the Democratic Republic of Congo (DRC) and Sudan, which seems at odds with the high investment risks and very low installed capacity in both countries[2]. Accounting for CoC differences between countries changes the results dramatically, as we show in Fig. 1. We therefore argue that using uniform CoC can lead to distorted policy recommendations.

Wind power, PV, and hydropower are capital intensive, making the CoC a major determinant of these technologies' LCOE[3–7]. While Bogdanov and colleagues mention CoC as a "major factor of uncertainty", they assume a uniform CoC of 7% throughout the entire analysis. In reality, however, the CoC strongly varies across countries[8]. While the time value of money might be uniform, the risk premium for long-term investments varies due to differences in macroeconomic stability, political uncertainties, and the maturity of financial markets in different countries[3,9,10].

Figure 1a shows that risk spreads across 152 countries vary from 0 to 22.1% according to common metrics. Figure 1b illustrates the effect of the country risk spread for the three most expensive (Italy, South Korea, Switzerland) and the three least expensive (DRC, Peru and Sudan) solar PV-based energy systems in 2050 as reported in Bogdanov et al. It compares the 2050 LCOE of solar PV assuming a 7% CoC versus a country-specific CoC. Apart from the CoC, our calculation uses the input parameters from Bogdanov et al. To arrive at the country-specific CoC, we use the 10-year average (2008–2017) CoC for solar PV in Germany (3.1%)[11] to establish a lower bound. To this lower bound, we add a country premium corresponding to Moody's country rating for each country other than Germany (zero premium in the case of Switzerland)[12].

The results show that solar PV LCOEs are between 7 and 30% lower for the set of industrialised countries and up to 170% higher for the set of developing countries when assuming a country-specific CoC. These numbers are similar and slightly more pronounced when estimating 2015 instead of 2050 LCOEs (−30 to +180%). Importantly, the LCOE in the three industrialised countries are substantially lower than those in DRC or Sudan, when using country-specific CoC, turning the results reported in Fig. 2 of Bogdanov and colleagues upside down. Of the three analysed developing countries, Peru is the only case for which assuming country-specific financing costs would in fact result in lower costs than those reported by Bogdanov and colleagues (−18%). Based on these results, we argue that one can expect the following pattern: 2050 LCOEs of renewables in most developing countries would likely be substantially higher and in most industrialised countries substantially lower than those projected by Bogdanov and colleagues.

The implications are stark. Using uniform CoC may underestimate the cost of RE in developing countries and overestimate it in industrialised countries. Consequently, such analysis conceals the important role of de-risking policies in enabling RE deployment in developing countries[3]. At the same time, the bias may undermine policymakers' efforts to push forward the RE expansion in industrialised countries, e.g., by pointing to seemingly more cost-efficient options in developing countries. Importantly, our critique of (quasi-)uniform CoC in country-level cost comparisons is not confined to Bogdanov and colleagues but applies to other models, such as the LCOE models of the International Energy Agency (IEA) or the International Renewable Energy Agency (IRENA) too. The IEA uses a CoC of 7% for OECD countries and 8% for the rest[13]. The IRENA uses a CoC of 7.5% for OECD countries and China and 10% for the rest[5]. For modelling and interpreting global outcomes, the use of uniform CoC is not necessarily problematic. However, our above calculations demonstrate that if the models are used to compare

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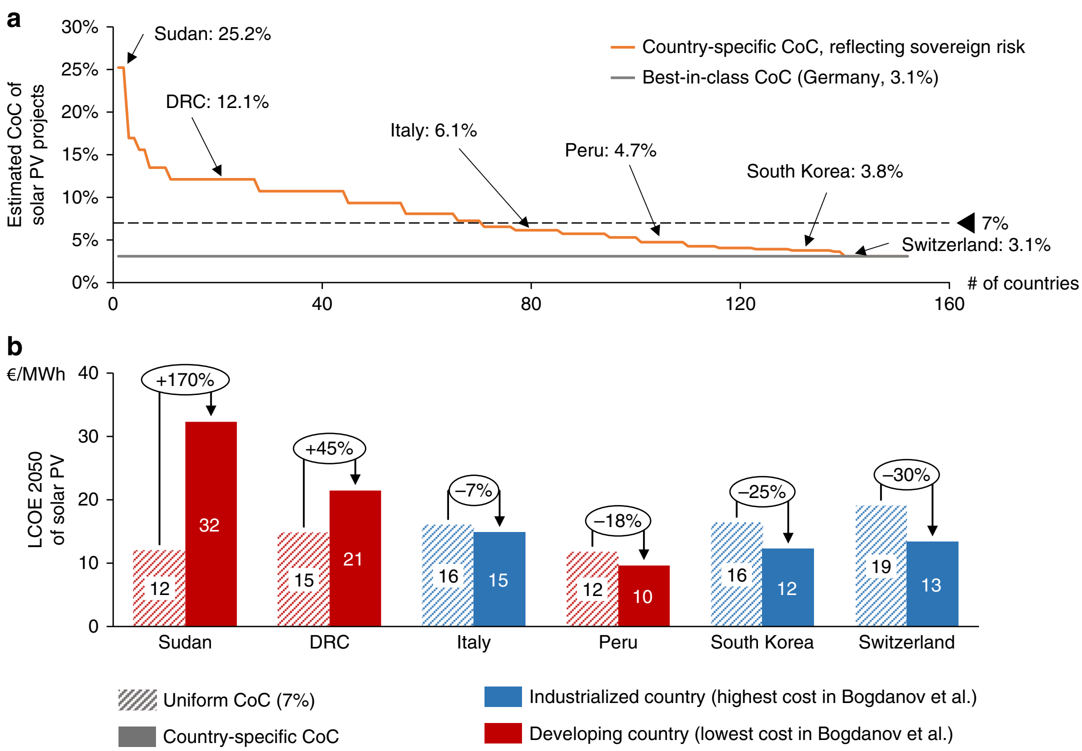

Fig. 1 Country-specific solar PV CoC and its effects on 2050 LCOE in six countries with the highest and lowest solar energy system cost as reported in Bogdanov et al. **a** Calculated country-specific CoC for 152 countries based on a risk-free CoC of 3.1% and risk premium according to Moody's sovereign ratings. **b** Change in 2050 solar PV LCOE due to changes in the CoC. The LCOE calculation shows values for single-axis tracking solar PV systems, which is the most deployed type in Bogdanov et al. Note that we do not perform an energy system calculation but for illustrative reasons focus on the LCOE. Grid and storage infrastructure investments are similarly affected by CoC differences

country-specific RE LCOEs as an output, they should clearly use country-specific CoC.

Empirically, the CoC also varies between technologies, though technology spreads are small compared with country spreads[8], especially for mature technologies (which seems a fair assumption for the 2050 scenario). It should also be noted that CoC can change over time—not just in terms of the general interest rate level, but also the risk spreads between countries. There are indeed examples of low- or middle-income countries that were able to reduce their risk spreads compared with industrialised countries to almost zero over a few decades. For example, from 1998 to 2019, South Korea improved its credit rating from Ba1 to Aa2, which corresponds to a 2.3%-point risk-spread reduction[12,14]. However, South Korea is one of the very few countries that have escaped the low- or middle-income traps during the last few decades[15]. Such strong improvements require overcoming many institutional and socioeconomic challenges. A case in point is the persisting large difference in solar PV CoC between Eastern and Western countries of the European Union[8].

Therefore, we believe that in projection studies such as Bogdanov et al., where no better knowledge is available, the prudent approach is to assume that current economic differences persist, reflected in the respective CoC differences. To study the sensitivity of the model towards this assumption, we also calculate the LCOEs assuming a halved spread between Germany and developing countries. The underestimation of LCOEs in high-risk countries is lower, but differences compared with the uniform CoC remain (+64% for Sudan, +5% for DRC). However, the past has shown that risk spreads can also increase and it is far from certain that developing countries will consistently be able to close the gap to industrialised countries. Uniform CoC (zero risk spreads) assumes global convergence to similar macroeconomic stability, political uncertainty, etc. and should be labelled accordingly.

To conclude, we argue that (renewable) energy system models that compare countries—and particularly countries across different income and investment risk classes—should always employ country-specific CoC. Using uniform CoC may result in distorted results and policy implications.

Data availability

The data and the underlying model are available from the authors upon reasonable request.

Received: 9 May 2019; Accepted: 6 September 2019;
Published online: 09 October 2019

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Acknowledgements

This work was supported by the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract number 16.0222. The opinions expressed and arguments employed herein do not necessarily reflect the official views of the Swiss Government. This work was conducted as part of the European Union's Horizon 2020 research and innovation programme project INNOPATHS under grant agreement no. 730403.

Author contributions

F.E., B.S. and T.S.S. conceived the idea. F.E. carried out the analysis. F.E., B.S. and T.S.S. wrote the paper. T.S.S. secured project funding.

Competing interests

The authors declare no competing interests.

Additional information

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Peer review information *Nature Communications* thanks Frans G Berkhout for their contribution to the peer review of this work.

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Annex II: Curriculum Vitae

Florian Egli

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PROFESSIONAL EXPERIENCE

Since Apr 17	**ETH Zurich** PhD Candidate with Prof. Tobias Schmidt, Energy Politics Group • Works on renewable energy finance in close contact with investors • Part of the EU Horizon2020 project INNOPATHS
Since July 13	**foraus – Swiss foreign policy think tank** *Vice President; July 2013 - Sept. 2015 Head of Region Bern* • Co-founded and professionalized a grassroot movement with 1000+ members • Develops strategy and oversees staff of 10+ employees in 2 offices • Facilitates design thinking workshops and moderates high-level panel discussions
Oct. 16 – Apr 17	**Antenna Foundation** • Business development for Oolux SA - solar lighting solution for West Africa
Sept. 15 - Sept. 16	**Mercator Fellow on Innovation and Climate Change** • *Visiting Fellow, **E3G** (No.1 UK Environmental Think Tank, July 16 – Oct. 16)* • *Visiting Fellow, **Aggrigator Inc.** (Bay Area tech start up in agriculture, May 16 – July 16)* • *Monitoring and Evaluation Consultant, **Senegalese Ministry of the Environment and Sustainable Development** (Agence de la Grande Muraille Verte, Feb. 16 – May 16)* • *Climate Finance Advisor, **Swiss Federal Office for the Environment** (Sept. 15 - Dec. 15)*
Aug. – Dez. 15 July – Oct. 14	**OECD Organization for Economic Cooperation and Development, Paris** *External Consultant; prior: Research Assistant & Green Growth Intern* • Lead author of an OECD working paper on breakthrough inventions and an OECD issue note on green innovation strategies and firm dynamics • Worked empirically with patent data • Provided OECD Input for EU Ministerial Conference (Environment and Labour) in Milan • Developed strategy for the Green Growth Synthesis Report 2015
Jan. 13 – Aug. 15	**Ecoplan AG, Economic Research and Policy Consultancy, Bern** *Consultant* • Conducted econometric and political analysis for the national government, cantons and cities (Bern, Geneva) • Conceptualized and implemented survey designs and conducted interviews

EDUCATION

2013 – 2015 **Graduate Institute of International and Development Studies (IHEID)**
MA in International Economics, summa cum laude, GPA 5.54 (max. = 6)

- Thesis: Policies for a green world – The example of technological change in the steel industry
- Teaching assistant in the graduate course "Political Economy of Resources, Environment and Development" with Prof. Timothy Swanson
- Research affiliate for the Swiss National Science Foundation project "Innovation, Diffusion and Green Growth"

2010 – 2013 **University of Bern and TSE Toulouse School of Economics (Erasmus)**
BSc in Economics (minor in ecology), insigni cum laude, GPA: 5.6 (max. = 6)

- Thesis: The Chicago Plan and 100% Reserves in the Case of Switzerland
- Teaching assistant in the undergraduate course "Micoreconomics" with Prof. Gunter Stephan
- Research assistant for a project on economic benefits of cultural activities of a large foundation

ACADEMIC SERVICES

- **Supervision** of master students and semester projects.
- **Referee** activity for: Nature Energy, Environmental Research Letters, Energy Econoimcs, Environmental Research Communication, Energy Research & Social Science, Journal of Sustainable Finance & Investment, Utilities Policy
- **Presentation** on academic conferences (2018 & 2019): Strommarkttreffen, GIZ, Berlin/Germany; 16th IAEE European Conference, Ljubljana/Slovenia; 24th EAERE Annual Conference, Manchester/UK; 2nd Sustainable Finance Conference, Vaduz/Liechtenstein; 7th ISEFI Annual Conference, Paris/France; Wind Europe 2019, Bilbao/Spain; Frontiers in Energy Research, Zurich/Switzerland; 11th IEWT Annual Conference, Vienna/Austria; 1st Energy Innovation Academy, Florence/Italy; 1st GRASFI Annual Conference, Maastricht/Netherlands; Fossil Fuel Supply and Climate Policy Biannual Conference, Oxford/UK; 41st IAEE International Conference, Groningen/Netherlands.

OUTREACH ACTIVITIES

- Co-Founder **ETH Energy Blog**: https://blogs.ethz.ch/energy/
- Innovation expert / mentor **Sustainable Development Solutions Network Youth** (SDSN Youth): https://www.youthsolutionshub.org/
- Expert **Climate KIC The Journey** (2017, 2018, 2019): https://journey.climate-kic.org/
- Expert **Sustainable Development Solutions Network Youth**: https://www.youthsolutionshub.org
- Co-Founder **Sustainable Fintech**: https://sustainablefintech.ch
- Co-Founder World Economic Forum (WEF) **Global Shapers Bern**: https://www.globalshapersbern.org/
- Regular **workshop moderation and design** (e.g., Humanitarian Diplomacy Lab with ICRC, Sustainable Fintech with leading Swiss banks, Sexual Harassment with Le Temps): https://global-diplomacy-lab.org/activities/open-situation-room-in-geneva/
- Regular **commentator in the media** on foreign policy and climate issues (e.g., Die Zeit, Republik, Swiss National TV and Radio (SRF), Tagesanzeiger, Monocle Radio 24, etc.)
- Member **Swiss Study Foundation** for Academic Excellence since 2009
  - Recipient of a scholarship to work at the OECD in 2014

PUBLICATIONS

Peer-reviewed

Egli, F. (2020). Renewable energy investment risk : An investigation of changes over time and the underlying drivers. ***Energy Policy***, *140*, 111428. https://doi.org/10.1016/j.enpol.2020.111428

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Polzin, F., Egli F., Steffen, B., Schmidt, T.S. (2019). How do policies mobilize private finance for renewable energy?—A systematic review with an investor perspective. ***Applied Energy***, 236, 1249-1268. https://doi.org/10.1016/j.apenergy.2018.11.098

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Best paper award GEE INREC 2018

Book chapters

Egli, F., Steffen, B. & Schmidt, T.S. (forthcoming, 2020). Cost of capital for renewable energy – the role of industry experience and future potentials. In *Green Banking* (ed. Böttcher, J.). De Gruyter: Berlin, Germany.

Steffen, B., Egli, F. & Schmidt, T.S. (forthcoming, 2020). The role of public banks in catalysing private renewable energy finance. In *Renewable Energy Finance* (ed. Donovan, C.). Imperial College Press: London, UK.

Egli, F. (forthcoming, 2020). State Investment Bank: An effective tool to finance sustainability?. In *Financing the low-carbon economy transition – mapping innovative instruments*. Swiss Sustainable Finance: Geneva, Switzerland.

Hofstetter, D. & Egli, F. (forthcoming, 2020). Transformation Capital – A Systemic Investment Logic. In *Financing the low-carbon economy transition – mapping innovative instruments*. Swiss Sustainable Finance: Geneva, Switzerland.

Policy and working papers

Egli, F., Steffen, B., Schmidt, T.S. (2019). Learning in the financial sector is essential for reducing renewable energy costs. ***Nature Energy***, 4, 835-836. https://doi.org/10.1038/s41560-018-0277-y

Egli, F. & Maule, S. (2017). Missing in Action: The Lack of ESG Capacity at Leading Investors***. E3G Briefing Paper.*** London, UK.

Stünzi, A., Egli, F. & Jönsson, O. (2017). Neue Wege in der Schweizer Klimapolitik. ***Foraus Policy Brief.*** Berne, Switzerland.

Egli, F. & Johnstone, N. (2015). Emerging Technologies & Firm Dynamics: The Implications of Green Growth. ***OECD Issue Note Green Growth and Sustainable Development Forum***. Paris, France.

Egli, F., Johnstone, N. & Menon, C. (2015) Identifying and inducing breakthrough inventions: An application related to climate change mitigation. ***OECD Sci. Technol. Ind. Work. Pap****.*
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