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Estimating the cost of capital for renewable energy projects

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ABSTRACT

Many models in energy economics assess the cost of alternative power generation technologies. As an input, the models require well-calibrated assumptions for the cost of capital or discount rates to be used, especially for renewable energy for which the cost of capital differs widely across countries and technologies. In this article, we review the spectrum of estimation methods for the private cost of capital for renewable energy projects and discuss appropriate use of the methods to yield unbiased results. We then evaluate the empirical evidence from 46 countries for the period 2009–2017. We find a globally consistent rank order among technologies, with the cost of capital increasing from solar PV to onshore wind to offshore wind power. On average, the cost of capital in developing countries is significantly higher than in industrialized countries, with large heterogeneity also within the groups of industrialized or developing countries.

1. Introduction

With power generation being the largest contributor to anthropogenic CO_2 emissions, decarbonization of the sector ranks high on policy agendas worldwide. To this end, many countries are targeting the deployment of renewable energy (RE) technologies, some of which have grown rapidly since the turn of the century. To achieve the goals of the Paris Agreement, however, the deployment of RE must be even further accelerated, as illustrated by the fact that emission pathways in line with the agreement's 1.5–2 °C target always assume a strong increase in wind and solar capacity (Luderer et al., 2018). These quantitative results are supported by analytical analyses which show that early investments in clean energy plants can lead to pathways that reduce emissions efficiently in the presence of knowledge accumulation (Acemoglu et al., 2012; Goulder and Mathai, 2000) and long-lived abatement capital (Vogt-Schilb et al., 2018).

As the expansion of RE generation requires large investments, a sound understanding of the costs and benefits of RE technologies is necessary to effectively decarbonize the power sector on an efficient path. With the growing deployment of RE, energy economists have studied the cost of RE generation from various angles, informing policymakers and investors about the cost and value of different RE technologies (cf. e.g. Borenstein, 2012; Fell and Linn, 2013; Hirth, 2013; Joskow, 2011; May, 2017; Scholz et al., 2017; Zhang et al., 2016). By now, estimations of RE generation cost from economic modeling have become an integral part of long-term energy scenarios that inform the global climate policy discourse (cf. Creutzig et al., 2017; Luderer et al., 2017; Pietzcker et al., 2017).

In model setups that compare capital-intense RE technologies with less capital-intense fossil fuel–based technologies, a precise representation of the cost of capital for RE projects (which is reflected in discount rates) is a prerequisite for meaningful quantitative results. The reason is that deploying RE technologies requires large up-front investments that must be financed. Thus, the cost of capital makes up a significant part of the lifecycle costs of RE projects; for example, in recent years, for solar photovoltaics (PV) in Germany the cost of capital totaled 12–37% of the levelized cost of electricity (LCOE) (Egli et al., 2018). In developing countries like Brazil or India, cost of capital can even account for 50% of the LCOE for solar PV (Schmidt, 2014). Borenstein (Borenstein, 2012) illustrates how solar PV generation cost changes immensely

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depending on the interest rate assumed. Fossil fuel–based power generation, in contrast, is less affected by its cost of capital as a large part of the lifecycle costs are fuel expenditures which do not have to be financed up front (Schmidt, 2014). Accordingly, model-based research has illustrated that cost-efficient technology choices are highly sensitive to the assumed cost of capital or discount rate (Hirth and Steckel, 2016; Iyer et al., 2015; Stocks, 1984; Sweerts et al., 2019).

From a theoretical point of view, an important difference needs to be made between the social and the private cost of capital. The *social* cost of capital, i.e. the discount rate that maximizes intertemporal social welfare, is required to derive socially optimal pathways, including for climate change mitigation investments. Theoretical and empirical work over the last decades made progress in quantifying the social cost of capital, though substantial disagreement on the appropriate choice of parameters remains (cf. e.g. Arrow et al., 2014; Dietz et al., 2018; Weitzman, 2007). In contrast, the *private* cost of capital, i.e. the discount rate used in private investment appraisals, is required to model investment decisions by firms that choose between alternatives (such as different power generation technologies) in a world that deviates from the theoretical optimum. Common applications in energy economics include the projection of RE expansion pathways, the assessment whether certain carbon emission targets will be reached, and the ex-ante evaluation of policy interventions that affect the relative revenue or cost position of technologies. For discounting in such applications, it is not the (normative) social discount rate that matters, but the (empirical) private discount rate for potential investment projects. This article focuses on the private discount rate, more commonly referred to as cost of capital in an empirical context.[1]

Although sound assumptions about the private cost of capital are crucial for sensibly calibrated models, suitable empirical data is hardly available to researchers (Donovan and Nuñez, 2012; Egli et al., 2018). The key reason is that many RE projects are realized using project finance in which the financial details remain private information (Steffen, 2018). Unlike in corporate finance setups in which the cost of capital is often visible from publicly traded securities, typical RE project finance structures combine non-traded equity investment with bank debt, and “financing models used by companies are confidential, making it impossible to know or to verify the actual values used by project developers” (Dobrotkova et al., 2018, p. 136). Cost of capital is typically considered a trade secret, and thus, is often not disclosed (Krupa and Harvey, 2017). Although the lack of transparency is less of an issue for RE investors (who know their cost of capital for a specific project), it is a challenge for researchers and policymakers alike (Egli et al., 2018). In particular, assuming a standard discount rate is often inappropriate in energy system models given the high sensitivity of results to this parameter (Iyer et al., 2015; Schmidt, 2014).

Further complicating the matter, empirical data show large variations in RE cost of capital along several dimensions. Most importantly, the cost of capital differs widely between countries (Angelopoulos et al., 2016; Egli et al., 2019). In many cases, the spread in the cost of capital is the determining factor for LCOE differences between countries, not solar irradiation or wind resources (Dobrotkova et al., 2018; Ondraczek et al., 2015). Even within countries, there might be structural differences between different RE technologies, and the cost of capital can change over time due to RE-specific effects or economy-wide variations in the interest rate (Egli et al., 2018; Kirkpatrick and Bennear, 2014).

Realizing the need for a better understanding of RE cost of capital, a number of scholars recently started to estimate such data in various ways (see Section 5). However, besides considering a very diverse set of countries and technologies, studies used different measures for the cost of capital, making it hard to compare the estimates. The scholars also applied very different estimation methods, ranging from financial market econometrics to qualitative interviews. Thus, although progress has been made in estimating RE cost of capital in specific contexts, a consistent picture of the overall state of knowledge is missing. Making appropriate assumptions about the cost of capital in investment and energy system models remains challenging. To address this challenge, here we present a systematic review of the global empirical evidence on RE cost of capital, to answer two research questions:

1. Which methods are appropriate for estimating the cost of capital for RE projects?
2. What is the state of the empirical knowledge?

Based on the review results, we discuss the large heterogeneity in the cost of capital that can be observed, and implications for energy system modelers, energy economists more generally, and RE policy makers. The remainder of the article is structured as follows: Section 2 provides a conceptual background concerning the cost of capital for RE projects. Section 3 outlines the methodology of this review, and Section 4 describes the literature base we analyzed for both research questions (RQ). Results concerning appropriate estimation methods (RQ 1) are summarized in Section 5, an empirical analysis of the quantitative evidence (RQ 2) is presented in Section 6. The final section concludes.

2. Characteristics of cost of capital for renewable energy

Understanding investment in and financing of renewable energy assets is of interest for scholars in several economics fields (e.g., energy and environmental economics, energy system modeling, and financial economics) with differing conceptualizations of the cost of capital or discount rates. For clarity of analysis, we provide a brief description of financing structures and cost of capital measures as understood in this article, and we summarize extant research on the expected heterogeneity in the cost of capital between renewable energy assets.

2.1. Financing structures for renewable energy projects

Similar to other infrastructure assets, power plants can be financed either through corporate finance structures (i.e., “on balance sheet”, for instance of a utility), or project finance structures (i.e., “off balance sheet”, in a new legal entity). While many fossil fuel–based power plants have traditionally been realized by utilities in corporate finance structures, the surge of renewable energy investments over the last two decades was driven by a much broader set of sponsors drawing on project finance (Henderson, 2016; Steffen, 2018). In 2015, project finance was used in more than half of all new investment in RE projects worldwide, and in even higher shares in OECD countries (Steffen, 2018). Therefore, in this article, we focus on this RE-specific financing structure.

In project finance, the sponsor creates a self-contained legal entity (or special purpose vehicle, SPV) to hold the RE asset, which then is financed by debt and equity on the level of the SPV. For repayment, equity investors and debt providers depend solely on the future cash flows of the RE project, and cannot recourse on other assets of the project sponsor. Thus, the investment risk profile of the RE project, and the corresponding cost of capital, is specific to the individual investment project (Hainz and Kleimeier, 2012; Krupa and Harvey, 2017; Steffen, 2018).

2.2. Measures of the cost of capital

While various definitions for the private cost of capital exist (cf. Helms et al., 2015), here we follow the common economic understanding of “the expected rate of return that market participants require in order to attract funds to a particular investment” (Pratt and Grabowski, 2014, p. 3), expressed as percentage value. Describing the

[1] Note that private cost of capital are also often referred to as WACC (weighted average cost of capital); see Section 2.2 for a precise definition.

expected returns, the cost of capital is a forward-looking measure comprising the time value of money and a premium for risk (as well as potentially further factors, such as taxes or transaction costs). The cost of capital is equal to the discount rate as used in investment appraisals, such as net present value calculations.

For investments that use more than one type of capital (e.g., equity and debt), the overall cost of capital is a combination of the returns of the different components. In the most simple formulation, the weighted average cost of capital (WACC), sometimes termed "vanilla WACC" (Estache and Steichen, 2015), is defined as

$$\boldsymbol{WACC_{vanilla}} = \boldsymbol{\delta}\, \boldsymbol{C_d} + (\boldsymbol{1}-\boldsymbol{\delta})\boldsymbol{C_e}, \tag{1}$$

where δ is the debt share (in %), C_d is the cost of debt (in %), and C_e is the expected return on equity (in %). The vanilla WACC abstracts from any considerations of tax. In most countries, however, interest payments are tax-deductible expenses for companies; thus, debt comes with a tax benefit. This fact is reflected in the after-tax WACC

$$\boldsymbol{WACC_{after-tax}} = \boldsymbol{\delta}\, (\boldsymbol{1}-\boldsymbol{\tau})\, \boldsymbol{C_d} + (\boldsymbol{1}-\boldsymbol{\delta})\boldsymbol{C_e}, \tag{2}$$

where τ is the corporate tax rate. Hence, interest payable on debt is already factored in taxable profits here. In some cases (e.g., for regulators that want to define prices which allow a company to meet corporate tax liabilities and deliver a certain return on debt and equity), the pre-tax WACC is calculated as

$$\boldsymbol{WACC_{pre-tax}} = \boldsymbol{\delta}\, \boldsymbol{C_d} + (\boldsymbol{1}-\boldsymbol{\delta})\frac{\boldsymbol{1}}{(\boldsymbol{1}-\boldsymbol{\tau})}\boldsymbol{C_e}, \tag{3}$$

where $1\,/\,(1\text{-}\,\tau)$ is the tax wedge on the cost of equity. All three definitions are used in articles concerning renewable energy projects. As the debt share varies significantly between countries, between technologies, and over time, the advantage of tax-deductible interest payments must be considered for a meaningful comparison. Therefore, we follow the majority of the literature in using the after-tax WACC wherever possible in this review (note that $WACC_{pre\text{-}tax}$ and $WACC_{after\text{-}tax}$ can be converted into each other as long as the tax rate τ is known and constant over time).

Although the cost of capital is usually stated in nominal terms, in contexts with uncertain future inflation, sometimes, the deflated WACC is used to describe the cost of capital excluding inflation expectations. The two values can be converted using Fisher's equation

$$\boldsymbol{1} + \boldsymbol{WACC^{nominal}} = \left(\boldsymbol{1} + \boldsymbol{WACC^{real}}\right)(\boldsymbol{1} + \boldsymbol{w}), \tag{4}$$

where w is the expected inflation rate. Finally, all values can refer either to investors in the local currency (the standard case considered in this review) or to investors from a hard currency area, by including the premium they require for investments in the local currency (Shrimali et al., 2013).

2.3. Expected heterogeneity among projects

It is common in financial economics to conceptually decompose the expected rate of returns into a risk-free rate (reflecting the time value of money) and a risk premium (reflecting the investment-specific risk (Pratt and Grabowski, 2014). While the risk-free rate should not differ between investment alternatives, it is primarily the risk premium that causes the variance in the observed cost of capital (differences in taxes and transaction costs can also play a role). A wide range of literature uses investor surveys to assess the nature of investment risks related to renewable energy assets (Angelopoulos et al., 2016; Egli, 2020; Lüthi and Wüstenhagen, 2012; Salm, 2018; Salm and Wüstenhagen, 2018; Waissbein et al., 2018, 2013). These studies provide an indication of which factors lead to differences in the cost of capital between groups of projects (notwithstanding idiosyncratic factors of each setting). Three dimensions are pertinent to define our analysis.

First, the *country* in which a RE project will be undertaken affects the overall investment risk. Investors consider country-level aspects, such as macroeconomic stability and political uncertainties for long-term commitments (Steffen and Papakonstantinou, 2015; Waissbein et al., 2013). For RE projects in contexts where the cash flow depends on payments from a public entity (e.g., from a feed-in tariff or from a power purchase agreement, PPA), also the experience with the RE-specific policy framework matters (Egli et al., 2018; Estache and Steichen, 2015; Lüthi and Wüstenhagen, 2012). An investor's perception of risks related to the regulatory framework can thereby be moderated by individual worldviews (Chassot et al., 2014). Depending on the design of a feed-in tariff or a PPA, there might also be different levels of electricity market risk exposure for RE generation (Neuhoff et al., 2018; Polzin et al., 2019; Salm and Wüstenhagen, 2018). In addition, the general state of financial markets differs between countries, affecting capital-intense sectors, such as RE (Kim and Park, 2016).

Second, investment risk differs between different RE *technologies* (Polzin et al., 2019; Salm, 2018). For instance, the resource risk related to solar irradiation is typically lower than the resource risk related to wind (Tietjen et al., 2016). In addition, solar PV plants and wind turbines are based on very different operating principles, and thus, the operational risks (component failures, hazards, etc.) differ. Rotating equipment like a wind turbine is prone to more wear and tear as compared to photoelectric systems like solar PV, hence the share of uncertain component repairs in operating cost is much higher for wind turbines than for solar PV (Steffen et al., 2020).

Third, both country- and technology-specific investment risks can *vary over time* (Egli, 2020; Mazzucato and Semieniuk, 2018). As new technologies are deployed, they become increasingly mature, and investment risk decreases, because of proven track records and increased the availability of data for such track records (Egli et al., 2018). In addition, investors and banks become more experienced in financing RE projects, improving their risk assessment processes (ibid.). Changes in regulatory frameworks can likewise affect RE investment risks (Leisen et al., 2019). Finally, in addition to RE-specific factors, the general interest rate environment has changed considerably over the last few decades (especially following the 2007–2008 financial crisis), affecting RE cost of capital as well (Egli et al., 2018; Kirkpatrick and Bennear, 2014).

Taking these dimensions into account, in the following analysis we differentiate empirical estimates for the cost of capital by country, technology, and financing year. We also consider the impact of fluctuating general interest rates.

3. Methodology

This article is based on a systematic review of existing empirical studies that quantify the cost of capital for renewable energy projects. The methodology is summarized in Fig. 1. First, we compile a literature base of relevant articles in an explicit and reproducible way. Second, we evaluate the selected articles concerning the research methods that are used for estimating the cost of capital, categorize the methods, and discuss their usability and limitations (RQ 1). Third, we extract empirical data on the cost of capital, convert them into comparable quantities using additional assumptions where necessary, compile a database suitable for a meta-analysis (Hunter and Schmidt, 2004), and discuss the empirical results along descriptive charts and statistics (RQ 2). The individual steps are described in more detail in the following.

3.1. Compilation of the literature base

To select the relevant articles in a reproducible way, we draw on established protocols for systematic literature reviews in the social sciences (Petticrew and Roberts, 2006). The literature search and selection

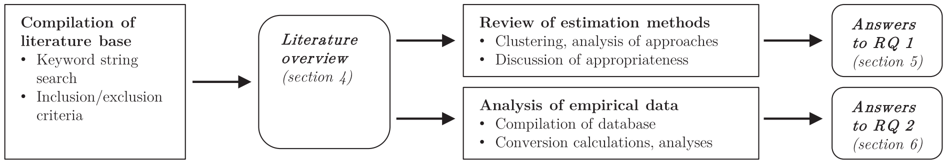

Fig. 1. Summary of review methodology.

thereby follows a sequence of steps with inclusion and exclusion criteria as follows: As the starting point, we consider all peer-reviewed literature (i.e., scientific journals, books, and conference proceedings) that had been published until the end of 2018 and are covered in the abstract database Scopus. Although in principle other types of archival documents (e.g., policy reports and press articles) contain information on the cost of capital for renewable energy projects, focusing on peer-reviewed literature means that all studies have been subject to some review concerning their methodological quality (Cooper, 1998), though of varying scrutiny depending on, inter alia, the journal. Limiting the analysis to peer-reviewed papers in the Scopus database also ensures full reproducibility of the literature search.

To address the research questions, we initially searched for articles where the title, abstract, or keywords included a reference to cost of capital (i.e., "cost of capital," or the more general terms "financing cost," "financing conditions") and a reference to the considered renewable energy technologies (i.e., "renewable energy" or "clean energy" or "sustainable energy" or "solar" or "wind"). While evaluating the corresponding initial list of 136 articles (described below), we conducted a follow-up snowball sampling round of the articles cited in the initial articles (Cooper, 1998), realizing that some relevant articles circumscribed the cost of capital without using these search terms. Therefore, we added the combination "risk premium" or "capital markets," and "investment" (which included all articles that appeared during the round of snowball sampling).[2] The resulting long list includes 182 papers.

For the long list of articles, meta-data was extracted and the abstracts were screened if the article could fulfil inclusion criteria in line with our research scope: quantifying the cost of capital of renewable energy-based power generation projects (solar PV, onshore wind turbines, and offshore wind turbines) for utility-scale assets. The short list includes 54 papers.

Next, we analyzed the full text of the short-listed papers in detail to assess the suitability of the methodologies and results for this review. We considered only articles that provide quantifications of the cost of capital based on empirical evidence (excluding, for instance, sensitivity analyses that study the impact of different WACC assumptions). Given that this review focuses on technology-specific WACCs for project-financed renewable energy plants (see Section 2.1), we also excluded articles that limit their discussion of the cost of capital to the company-level WACC of energy utilities (Helms et al., 2015; Weaver, 2012) or country-level assumptions of economy-wide WACCs (e.g. Labordena et al., 2017; Ondraczek et al., 2015). The remaining 19 articles (describing 18 studies) form the literature base for the review of the estimation methods (research question 1) and the analysis of empirical evidence (research question 2).

3.2. Review of estimation methods

For each of the 19 articles, we reviewed the methods used (short summaries in Table 1). Most of the studies provided this information as part of the main text or supplementary information. If questions remained, we referred to cited literature or contacted the corresponding authors to clarify. While reviewing the literature, we clustered the methods used in the articles by similarity and iteratively reduced the number of clusters until we arrived at the four basic approaches we describe in Section 5. The strengths and weaknesses of the different approaches are then discussed based on the discussions by the authors who used these approaches, specific criticism in other articles, and a holistic assessment taking into account the entire literature base.

3.3. Empirical analysis of cost of capital estimates

To summarize the empirical state of knowledge on RE cost of capital, quantitative results from all studies in the literature base are compiled in a database, including cost of debt, expected return on equity, debt share, and WACC (depending on what is reported in the studies). Values are considered separately per technology, per country, and per year. For each empirical value, we also included a description of the methodology used in the underlying article.

For studies that do not provide the $WACC_{after\text{-}tax}$, we converted the $WACC_{pre\text{-}tax}$ as described in Section 2.2, using corporate tax rate τ for the given country and year from KPMG (2018). Most studies report nominal values; in a few cases where only real WACCs (i.e., excluding inflation expectations) are provided, we also converted them into nominal WACCs for comparability, using the expected inflation rate w mentioned in the respective studies. Converted values are listed as separate entries together with the assumptions used. In total, the database includes 358 data points spanning the period 2000–2017 and covering 46 countries, and forms the basis for all empirical analyses in this article. It is provided in the Supplementary Information.

As mentioned in Section 2.3, the years since renewable energy projects were first rolled out are characterized by substantial changes in economy-wide interest rates, which must be considered when the cost of capital is compared over time. As a proxy, Fig. 2 shows the 12-months London Interbank Offered Rate (LIBOR), a common benchmark interest rate, in different currencies. The figure illustrates a regime change during the 2007–2008 financial crisis: LIBOR rates drop steeply in 2008, and then remain within a range of about −0.5% to 2%, although with some variation within that range. Therefore, when we aggregate the WACC estimates over time, we limit the analysis to the period since 2009 and consider $WACC_{after\text{-}tax}$ as *markups on the LIBOR* (i.e., $WACC_{after\text{-}tax}$ minus the LIBOR rate), a common approach used by banks and financial investors (Krupa and Harvey, 2017).[3]

4. Literature base

Table 1 provides details about all 18 studies that have been analyzed in detail.[4] Since the first publication in 2009 (an analysis of renewable energy costs in Italy), one to two relevant studies were published per year, before the research output increased sharply in 2017–2018 (eight studies were published, and thus, are the bulk of the empirical evidence). The authors' motivations for estimating the cost of capital differ: While early studies aim at generally decomposing the cost

[2] Final Scopus search string: TITLE-ABS-KEY(("cost of capital" OR "financing cost" OR "financing conditions" OR ("risk premium" AND "investment") OR ("capital markets" AND "investment")) AND ("renewable energy" OR "clean energy" OR "sustainable energy" OR "solar" OR "wind"))

[3] We use the 12-months LIBOR in GBP for the United Kingdom, in EUR for other European countries, and in USD for non-European countries.

[4] One study (entry no. 4) is described in two separate articles listed in Scopus.

Table 1
Empirical coverage of articles included in the review.

No	Reference	Technologies	Countries	Years	Estimated cost of capital components				Estimation method
					CoD	CoE	DS	WACC	
1	(Lorenzoni and Bano, 2009)	Solar PV, onshore wind, other (hydro)	Italy	2007	x	x		x	Elicitation of cost of capital components of unspecified project-financed plants from financial institutions
2	(Szabó et al., 2010)	Solar PV, onshore wind, other (bioenergy)	Generic EU/United States	Unclear				x	Expert interviews to judge technology-specific risk adjustments to standard values, archival information
3	(Donovan and Nuñez, 2012)	Other (mix of renewables)	Brazil, China, India	2009		x			Estimates from financial market data, using the CAPM adjusted for downside beta characteristics in emerging markets
4	(Wood and Ross, 2012)	Onshore wind, offshore wind	Denmark, Germany, Netherlands, Spain, Sweden, Switzerland, United States	2008	x	x	x	x	Compilation from national authorities as part of an International Energy Agency (IEA) task, drawing on elicitation of financial details of specified actual projects, or expert interviews
5	(Ardani et al., 2013b, Ardani et al., 2013a)	Solar PV	United States	2012				x	Expert interviews with various market participants (including developers and financiers), and archival information
6	(Shrimali et al., 2013)	Solar PV, onshore wind	India	2010–2011	x	x	x		Elicitation of cost of capital components from developers of specified projects, re-engineering of debt share
7	(Estache and Steichen, 2015)	Solar PV, offshore wind, onshore wind, other (biomass)	Belgium	2012				x	Estimates from financial market data using the CAPM
8	(Kitzing and Weber, 2015)	Offshore wind	Germany	2014	x	x	x	x	Estimates from financial market data, and archival information
9	(Angelopoulos et al., 2016)	Onshore wind	26 EU member states	2014	x	x	x	x	Expert interviews, using estimates from financial market data as the starting point for discussion
10	(Voormolen et al., 2016)	Offshore wind	Belgium, Denmark, Germany, Netherlands, United Kingdom	2012				x	Expert interviews to judge country-specific risk adjustments, archival information including financial modeling by BNEF
11	(Angelopoulos et al., 2017)	Solar PV, onshore wind	Greece	2014–2016	x	x	x	x	Same as no. 9
12	(Krupa and Harvey, 2017)	Other (mix of renewables)	United States	2016	x	x			Expert interviews and archival information
13	(Kumar et al., 2017)	Solar PV, onshore wind, other (biomass)	Cambodia, China, India, Malaysia, Thailand, Vietnam	2016	x		x	x	Expert interviews with one country expert for each country, and archival information
14	(Werner and Scholtens, 2017)	Onshore wind	Germany	2000–2013				x	Estimates from financial market data
15	(Apostoleris et al., 2018)	Solar PV	Saudi Arabia, United Arab Emirates	2015, 2017	x		x		Analysis/re-engineering of a financial model for winning auction bids, based on archival information
16	(Dobrotkova et al., 2018)	Solar PV	Brazil, Chile, El Salvador, Guatemala, India, Jamaica, Mexico, Peru, South Africa, Uganda, United Arab Emirates, Zambia	2013–2016				x	Analysis/re-engineering of a financial model for winning auction bids, based on archival information and expert interviews
17	(Egli et al., 2018)	Solar PV, onshore wind	Germany	2000–2017	x	x	x	x	Elicitation of cost of capital components of 133 projects from financial institutions (banks and investors)
18	(Partridge, 2018)	Onshore wind, other (coal, gas)	Denmark, India, United States	2015, 2017	x	x		x	Estimates from financial market data

Note: CoD = cost of debt, CoE = cost of equity, DS = debt share, WACC = weighted average cost of capital.

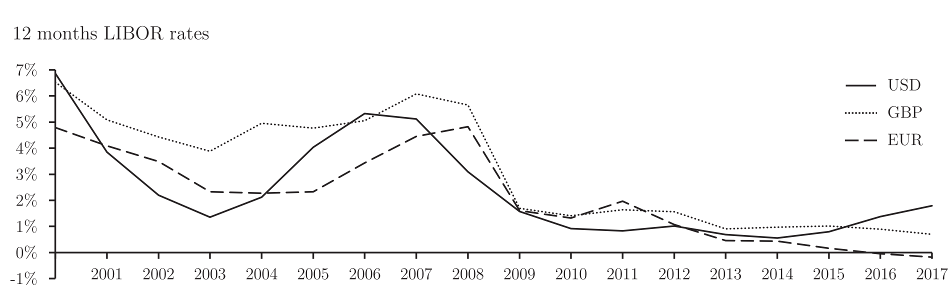

Fig. 2. General interest rate level over time.

structure of renewable energy projects and discuss cost-reduction pathways (e.g., Lorenzoni and Bano, 2009; Wood and Ross, 2012), several recent articles focus narrowly on RE cost of capital (Angelopoulos et al., 2016; Egli et al., 2018). Accordingly, studies also vary in the extent to which the cost of individual capital components is being estimated (see Table 1).

Concerning technologies, onshore wind projects have been analyzed in 11 studies, solar PV projects in 9 studies, and offshore wind projects in 4 studies, reflecting the different levels of maturity of the technologies. With respect to geography, half of the studies look at only a single country, and several others compare a small set of countries. Only three studies analyze five or more OECD countries (Angelopoulos et al., 2016; Voormolen et al., 2016; Wood and Ross, 2012), and only two studies analyze five or more developing countries (Dobrotkova et al., 2018; Kumar et al., 2017). Thus, the regional overlap is limited. We discuss the empirical data below, following the review of the estimation methods.

5. Estimation methods for RE cost of capital

To answer the first research question about which methods are appropriate for estimating the cost of capital for RE projects, we present and discuss the approaches taken in extant literature. Overall, the estimation methods can be clustered into four general approaches that are summarized in Fig. 3, structured in terms of the type of information used: *elicitation of project finance data* and *surveys of expert estimates* aim at gathering new data at the level of analysis which is of final interest (i.e., project-level financing data). Given the challenges of retrieving information at this level, two other approaches use readily available data from other areas: information about the specific project (and the general RE market) for aspects other than the cost of capital in the *replication of auction results* or information about the cost of capital beyond the specific project in the case of an *analysis of financial market data*. The different approaches will be described in turn, followed by an overarching discussion of suitability for different settings.

5.1. Elicitation of project finance data

The most direct way to quantify RE cost of capital is to collect and analyze the cost of different capital components from specific RE project finance deals, as listed in a term sheet or other documents held at the involved financial institutions. As mentioned above, eliciting such information is often challenging given the confidential nature of project finance data (Dobrotkova et al., 2018; Egli et al., 2018; Krupa and Harvey, 2017). Nevertheless, several scholars succeeded in gathering such data, starting with Lorenzoni and Bano (Lorenzoni and Bano, 2009), who conducted a survey among investors in the Italian market and presented granular figures for the components of the cost of capital referring to "real project financed plants as confirmed by financial institutions" (p. 103). Beyond the technology and the financing year, no further details about the projects are being provided. In a related approach, the study edited by Wood and Ross (Wood and Ross, 2012) summarizes a formal task of the International Energy Agency (IEA, an intergovernmental organization) for which seven national authorities collected data, including the cost of capital. Some of the countries thereby provide cost of capital data from specified projects, while others rely on expert interviews (see Section 5.2). Shrimali et al. (Shrimali et al., 2013) elicit financial parameters for specified Indian wind and solar projects in interviews with the developers of these projects.

Because the cost of capital in project finance-structures is asset specific, the external validity of the estimates from the elicited deal data is a caveat. As Wood and Ross (Wood and Ross, 2012) note, it is hard to assess whether single projects or deals used to estimate cost data are representative of typical projects in the market, which is even more the case if the projects are not identified, as in Lorenzo and Bano (Lorenzoni and Bano, 2009). A way to address this challenge was presented by Egli et al. (Egli et al., 2018), who elicit data on a large number of German projects that fit pre-defined characteristics, such as size and technology.

5.2. Survey of expert estimates

Given the scarcity of deal data, many studies fall back on interviewing RE market participants for their expert estimates, often complemented by archival information (e.g., press articles that mention the debt share of prominent projects). Experts can include project developers, financiers, and consultants or academics. In contrast to project data elicitation, interviewees do not reveal data on specific projects they were involved in, but instead, estimate the typical cost of capital they observe in the market. Examples include Ardani et al. (2013b, 2013a), who interviewed 70 market participants in the United States; Krupa and Harvey (2017), who combine discussions with Unites States "sector participants" and archival information; Kumar et al. (Kumar et al., 2017), who communicated with a "country expert" for each market they analyzed; and some of the contributions in Wood and Ross (Wood and Ross, 2012).

Compared to the elicitation of project data from specific deals, a qualitative estimate of cost of capital can often be provided by a broader set of interviewees, which facilitates the interview process. However, selection criteria that are too vague might increase the uncertainty concerning the representativeness of the estimates. While a general agreement of interest rates and return expectations often exists among participants in well-developed markets, such agreement is less common in smaller and less mature markets (Angelopoulos et al., 2016). In the latter, expert interviewees might express more of a "gut feeling" about the cost of capital (i.e. a value based on their intuition, not based on data), or they are not able to provide an estimate at all.

To formalize the process of expert estimations, and to facilitate discussions in small or immature markets, some authors chose to provide benchmark rates to the interviewees as a starting point for discussion. Voormolen et al. (2016) discuss country-specific risk adjustments of a generic estimate from a financial data provider (details on method in 3E, 2013). Taking a different approach for a broad study of 26 countries, Angelopoulos et al. (2017, 2016) use a WACC estimate from financial market data (see Section 5.4) as a starting point for discussions with 80 experts. These experts were asked to provide a general assessment whether and in which direction the actual market conditions deviate

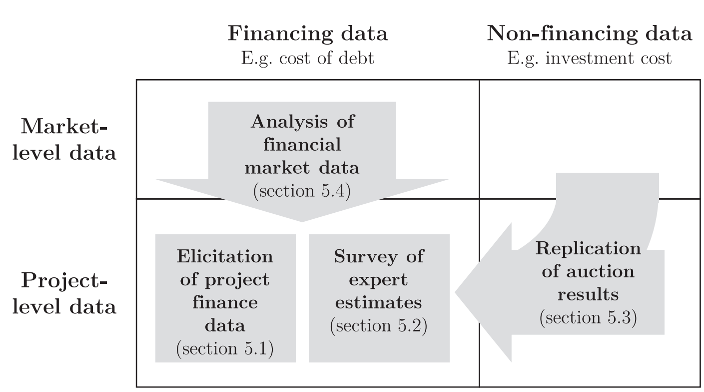

Fig. 3. Estimation methods by type of data used.

from the estimates, and by what order of magnitude (see also Ecofys, 2016). Using this mixed-methods approach, the authors estimate the components of the cost of capital for the broadest set of countries in all available studies, although with varying precision (as indicated by the broad ranges that are reported for some smaller markets). Finally, researchers also proposed conducting formal choice experiments (such as adaptive choice-based conjoint analysis) with investors. However, thus far, such experiments have been used to estimate risk premiums only, not the level of the components of the cost of capital (Salm, 2018; Salm and Wüstenhagen, 2018).

5.3. Replication of auction results

Recently, two studies (Apostoleris et al., 2018; Dobrotkova et al., 2018) used a different approach to estimate the cost of capital, drawing on non-financing data for projects that were awarded a PPA in a competitive auction. Since 2015–2016, policy support for solar and wind plants in many countries was shifted to competitive auctions for PPAs as a cost-effective mechanism for procuring renewable energy (Polzin et al., 2019). Noticing that some auctions revealed very low prices for PV generation in developing countries, Apostoleris et al. (Apostoleris et al., 2018) and Dobrotkova et al. (Dobrotkova et al., 2018) aimed at decomposing the cost structure of awarded projects.[5] They exploit the fact that much non-financing information on the winning bids is publicly available, including the remuneration per kilowatt hour generated (i.e., the awarded PPA) and cost data, such as capital expenditures (as PV modules and inverters are sold as global commodities at relatively transparent price levels). Thus, the cost of capital is often the only missing piece of information. By constructing an LCOE model to replicate the auction results, the authors estimate missing bits of information, such as the cost of capital. In an analysis of auctions in the Middle East, Apostoleris et al. (Apostoleris et al., 2018) mainly draw on archival information; the broader analysis for 13 developing countries by Dobrotkova et al. (Dobrotkova et al., 2018) complements such data with expert interviews at multilateral development banks.

5.4. Analysis of financial market data

All of the studies discussed thus far rely on some kind of project-level data. A separate stream of literature uses general financial market data to estimate RE cost of capital, more closely linked to the literature on the cost of capital for listed companies (Pratt and Grabowski, 2014). As typical RE projects are unlisted entities (SPV), their cost of debt and expected rate of return cannot be directly referred from the prices of traded securities; thus, authors use market data proxies. The expected return on equity and the cost of debt are estimated separately in all studies in this review. Therefore, we discuss the two components in turn. The debt share is typically not estimated from financial market data (as this project-specific parameter cannot be inferred from prices of traded securities), but taken from archival information or expert interviews as described above.

5.4.1. Market cost of debt

For listed companies, the cost of debt is directly available, for example, from the current interest expenses as per financial statements or from the yield of the company's publicly traded bonds (Pratt and Grabowski, 2014). Another proxy is the yield of bonds from a comparable company with a similar credit rating (Courtois et al., 2012). These approaches are also used to estimate the cost of debt for private RE assets, even though typically no bonds are issued but the projects are financed with bank loans. Estache and Steichen (Estache and Steichen, 2015) use information from financial statements of renewable energy companies active in Belgium, with the challenge of small sample sizes for individual technologies. Werner and Scholtens (Werner and Scholtens, 2017) use a general medium-term yield corporate bond index, claiming that these corporate bonds have a risk profile similar to that for wind energy projects. Partridge (Partridge, 2018) uses the spread of utility bonds over the risk-free rate, and adds an assumed surplus for renewable energy projects. A caveat to all these studies is whether the market proxies used are appropriate for estimating the cost of the bank debt for RE projects: Given the high debt share in project finance, a precise cost of debt figure is crucial for reliable WACC estimates.

A different approach to quantifying the cost of debt does not use the yield of traded bonds, but instead, estimates project finance-specific markups on the risk-free rate. In a study on Germany, Kitzing and Weber (Kitzing and Weber, 2015) use archival information on the typical swap premium (p_{swap}) and bank margin (BM) to be added to the risk-free rate (German government bonds):

$$\boldsymbol{C_d = r_f + p_{swap} + BM} \tag{5}$$

Their approach mirrors the interest rate calculation performed by a bank lending to an SPV, but hinges on the availability of bank margins and swap premiums which are often hard to obtain. Angelopoulos et al. (2017, 2016) also use the German government bond rate as the European risk-free rate, and add a CDS spread (the 10-year credit default swap quotation of the respective country), as well as an assumed "renewable energy project spread" (PS) that covers risk elements specific to renewable energy projects (e.g. uncertainty related to the renewable energy policy, compare Section 2.3):

$$\boldsymbol{C_d = r_f + CDS + PS}. \tag{6}$$

They also discuss alternative approaches, for instance, drawing on the LIBOR and spreads between government bonds of different countries, which all have in common that they are a combination of baseline rate, a country spread, and an RE project spread. These approaches can easily be applied to numerous countries, relying on the implicit assumption that the RE project-specific markup does not vary across borders.

5.4.2. Market return on equity

For estimating the cost of equity, the capital asset pricing model (CAPM), originally presented by Sharpe (1964) and Lintner (1965), is the dominant framework. It is used by almost all practitioners in corporate finance and financial advisory (Brotherson et al., 2013) despite shortcomings that have been acknowledged in the academic literature (mainly relating to stock return patterns that cannot be explained by CAPM, particularly for stocks in emerging markets) (Donovan and Nuñez, 2012; Fama and French, 1993). For RE projects, all reviewed studies drawing on financial market data use some variation of the CAPM, estimating the expected return on equity as

$$\boldsymbol{C_e = r_f + \beta(r_m - r_f)}, \tag{7}$$

where r_f is the risk-free rate, $(r_m - r_f)$ is the market risk premium, and β is a measure of the sensitivity of the expected asset returns to the expected market returns. The risk-free rate and the market risk premium apply to the market as a whole, but the beta factor is asset-specific, and thus, is the crucial parameter to be estimated.

For listed companies, betas are generally obtained by regressing individual stock returns against market returns, and quoted by financial data providers. For companies that are not publicly traded, the "pure-play method" is to consider the beta of a comparable company (or a group of companies) that has a similar risk structure (Courtois et al., 2012). For example, Estache and Steichen (Estache and Steichen, 2015) use a sample of Belgian RE generation companies, and Werner and Scholtens (Werner and Scholtens, 2017) consider independent wind energy developing firms. However, the two studies do not

[5] Although not within the technology scope of this review, Lilliestam and Pitz-Paal (2018) apply the same method for concentrated solar power (CSP) projects.

explicitly consider that project-financed RE assets likely have a much higher debt share than the comparable portfolio, which affects the equity beta. For such situations, Courtois et al. (Courtois et al., 2012) describe a process of first un-leveraging the beta to get a value that includes the pure business risk, and then re-leveraging the beta to the debt share of the entity under study. This approach is used by Angelopoulos et al. (Angelopoulos et al., 2017, 2016) and by Partridge (Partridge, 2018).

Although using beta as a risk measure is an established process for developed countries, the standard CAPM seems to be less suitable for developing countries and emerging markets (Courtois et al., 2012; Donovan and Nuñez, 2012). To improve estimates in these countries, Donovan and Nuñez use a "downside beta CAPM," which allows for non-normal return distributions as observed in emerging markets.

In sum, a variety of approaches use financial market data from traded securities as a proxy for the cost of debt and the return of equity of private RE projects. The potentials and limitations of these approaches, and of the previously discussed estimation methods, is discussed next.

5.5. Discussion of methods and their appropriateness

The review of methods emphasizes the challenges of estimating the cost of capital for privately held entities in a newly emerging industry such as RE. Researchers used different approaches depending on the individual studies' objectives, and the methods differ in terms of their appropriateness to yield unbiased estimates in different settings.

By directly addressing project-level financing data, both an *elicitation of project finance data* and *surveys of expert estimates* avoid inferences from other information on the variable of interest, and reduce the danger of systematically biased inferences. In return, however, these approaches raise questions about the representativeness of the gathered data, with non-representative samples potentially introducing a bias as well.

Although eliciting deal data for a large number of projects increases the representativeness of the estimates, the process is time-consuming, and is difficult to scale to a larger set of countries. As this method uses information from past deals only, it is also restricted to countries that have a substantial number of comparable projects to allow for a large n-analysis. Thus, the approach seems more suited for in-depth analyses of single markets, and less suited for larger cross-country analyses, especially if less mature RE markets are included.

Using expert estimates addresses some of these limitations; however, representativeness might be even more of an issue given the subjectivity involved. For example, meta-analyses of expert estimates in energy technology forecasting showed a rather low level of agreement between studies (Baker et al., 2015). Thus surveys of expert estimates seem less appropriate for obtaining precise values, but rather suited for an initial estimate of the cost of capital in a broader set of countries, particularly for immature markets where project-specific financing data are unavailable.

Estimates based on the *replication of auction results* are representative of the cost of capital in a certain auction round, as long as all bids that have been awarded a PPA are being analyzed. The precision of the estimates depends on the extent and quality of available non-financing information (which differs according to the specific country situation and actors involved). Naturally, the method is also limited to markets where PPA auctions are held. In these cases, the replication of auction results has shown to be a useful complement to expert interviews, by offering an empirical way to triangulate interviewee estimates.

The estimates based on *financial market data* build on a broad literature that quantifies the cost of capital for listed companies, drawing on the CAPM and its variants. By using accessible data, such as stock and bond quotations, these approaches seem suitable for analyses that compare the cost of capital in different countries for which market data are available from financial data providers. These approaches seem less appropriate for a precise comparison of technologies within a country, as typically the same proxies are used for solar and wind projects.

Well beyond RE assets, a general caveat of CAPM-based estimations is the limited empirical support for the model, as demonstrated by Fama and French (Fama and French, 1993) and others. Specific to RE projects, transferring insights from stocks and bonds to privately held project-financed assets is nontrivial, and the extant literature is partly based on strong assumptions to that end. The precision of financial market–based estimates hinges on the appropriateness of the market proxies for non-market assets. Further research drawing on the asset valuation literature is necessary to assess the appropriateness of assumptions made in the RE cost of capital estimates thus far.

In sum, it is promising that the nascent research on the cost of capital for RE projects has already developed a range of estimation methods each of which has been applied in several studies. The framework provided in Fig. 3 can help future researchers choose the estimation method depending on what type of data is best available, keeping in mind the suitability of the different approaches as discussed, and incorporating all the incremental improvements that previous studies made. Beyond refining the individual methods, future research could also further combine methods, for instance, by calibrating the premiums used in financial market data-based analyses more precisely based on rigorously elicited data from selected deals.

6. Analysis of empirical evidence

To answer the second research question, here we analyze the harmonized data on RE cost of capital, focusing on the after-tax WACC. First, we discuss the consistency of the estimates as they are reported by different studies. Second, we take into account past dynamics due to general interest rate changes. Third, we comment on the observed differences between countries and technologies.

6.1. Comparison of results from different estimation methods

Considering all available evidence, our literature base allowed to calculate $WACC_{after\text{-}tax}$ for solar PV projects in 23 different countries, for onshore wind projects in 28 countries, and offshore wind projects in 5 countries. Most data are for projects that were financed from 2010/2007 onwards (solar PV/wind) as shown in Figs. 4–6. For each technology, estimates of $WACC_{after\text{-}tax}$ per country over time are provided, with colors indicating the different estimation methods.[6] To illustrate developments over time and allow for the comparison of studies, three or more data points for the same country are connected by lines.

The first set of observations concern which estimation methods have been used for different technologies: While the elicitation of project data and surveys of expert estimates have been used universally, the replication of auction results so far has been limited to solar PV, a technology that experienced a number of record-breaking low bids which motivated two detailed analyses of the underlying factors. The analysis of financial market data, in contrast, has been used mainly for wind power (both onshore and offshore). It is not obvious why that is the case, and applying financial market-based analyses to solar PV projects seems an area for further research. In addition, all the available broader cross-country analyses draw on either expert estimates (Angelopoulos et al., 2016; Kumar et al., 2017; Voormolen et al., 2016; Wood and Ross, 2012) or auction result replication (Dobrotkova et al., 2018), and the use of financial market data for such purposes is pending.

Given the diverse set of countries that have been analyzed, the overlap in terms of different studies estimating WACCs for the same country, technology, and year is limited, such that a comparison of methods is only partly possible. For onshore wind projects, multiple studies cover

[6] Each study and year is shown as one data point (which might be based on several data points in the respective study.

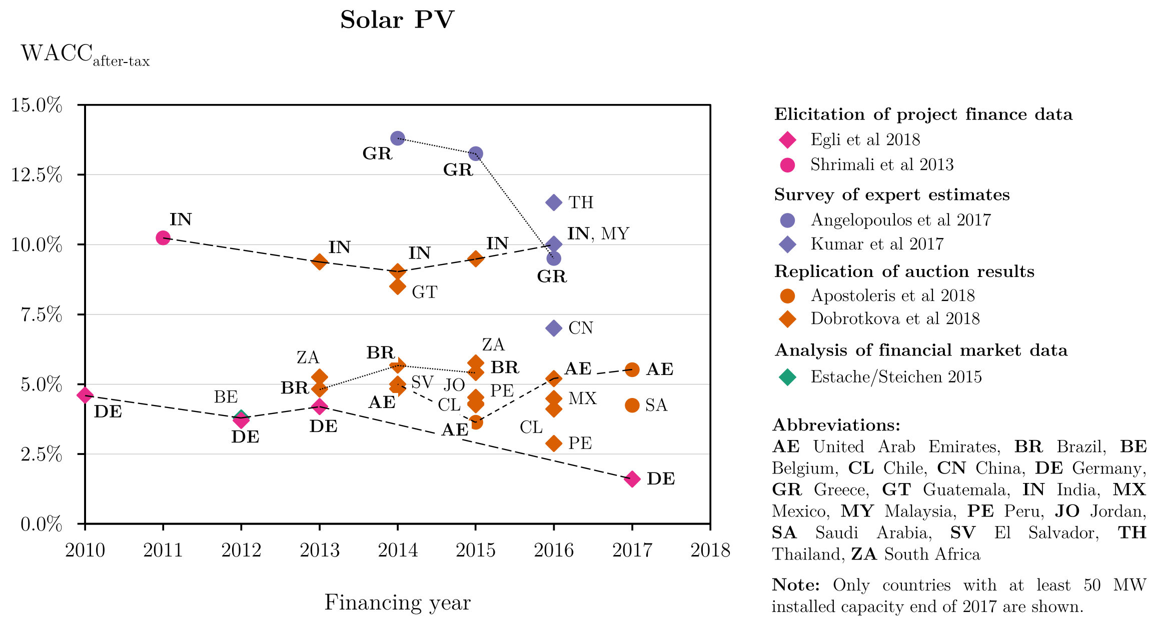

Fig. 4. Overview estimates of the WACC for solar PV projects.

the cost of capital for Germany: The financial market-based estimate by Werner & Scholtens (Werner and Scholtens, 2017), elicited deal data by Egli et al. (Egli et al., 2018), and expert estimates by Angelopoulos et al. (Angelopoulos et al., 2016) and Wood & Ross (Wood and Ross, 2012) are roughly consistent in the years in which the studies overlap (see Fig. 5). In addition, the estimates for onshore wind in Denmark from interviews (Angelopoulos et al., 2016) and financial market data (Partridge, 2018) are consistent. For solar PV projects, different estimates for India (Dobrotkova et al., 2018; Kumar et al., 2017; Shrimali et al., 2013) are all in the same magnitude (see Fig. 4). For offshore wind projects, only Belgian projects have been analyzed in two studies for the same year: The financial market–based estimate by Estache & Steichen (Estache and Steichen, 2015) thereby is more than 7 percentage point lower than the interview-based estimate by Voormolen (Voormolen et al., 2016), and overall, is a clear outlier (see the discussion of methodological shortcomings in Section 5.4.2).

6.2. Analysis of WACC markups

As shown in Figs. 4–6, the cost of capital within countries clearly varies over time, with a general downward trend over the period analyzed. To analyze RE-specific trends net of the development of economy-wide interest rates (see Section 3.3.), Fig. 7 provides the $WACC_{after\text{-}tax}$ *markup* for countries with at least three data points. Compared to the total WACC values shown in Figs. 4 and 5, the development of WACC markups over time is qualitatively the same. For example, there is still a clear decrease in Germany and Greece for both technologies (although at a slightly lower rate), likely reflecting financing

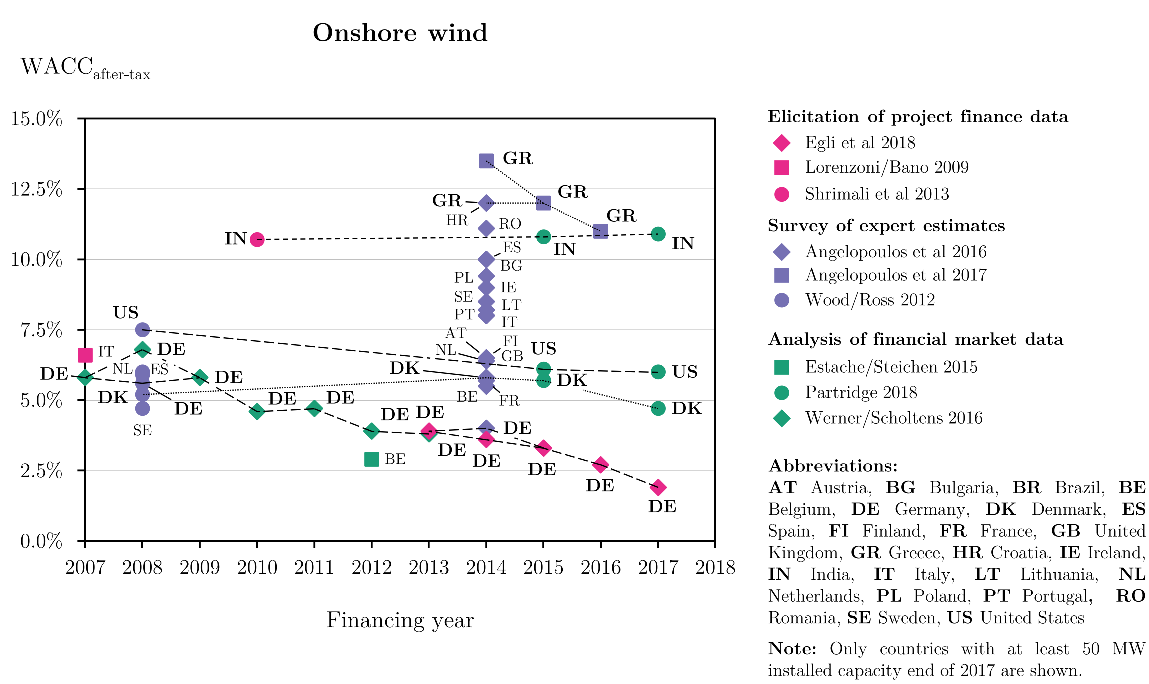

Fig. 5. Overview estimates of the WACC for onshore wind projects.

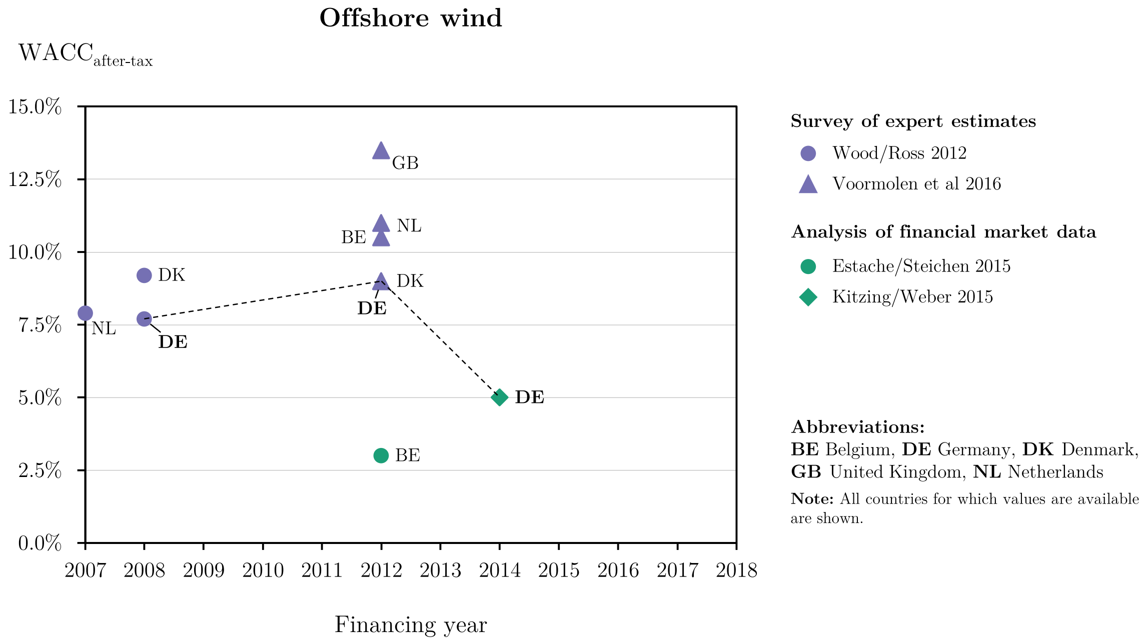

Fig. 6. Overview estimates of the WACC for offshore wind projects.

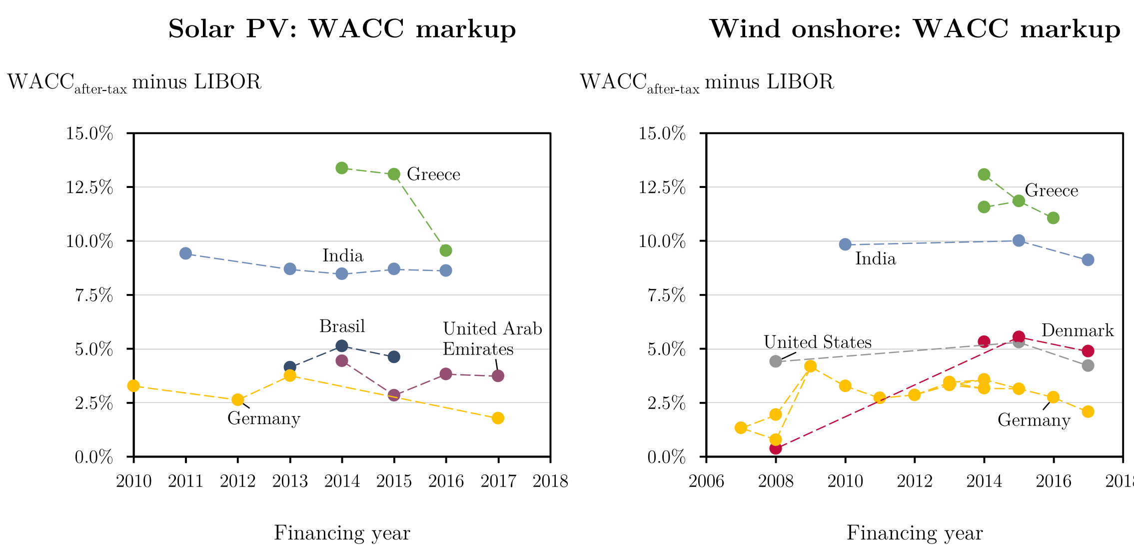

Fig. 7. General interest rate level and markups over time.

experience effects as described by Egli et al. (Egli et al., 2018). Only before 2009 (i.e., before the economy-wide interest rate regime changed) do the markup values look very different, approaching zero for onshore wind projects in Germany and Denmark. These values seem to be less comparable with the markups from later years.

6.3. RE cost of capital by country and technology

To further allow a comparison between countries, even if the estimates address different years, we averaged the WACC markup for the period 2009–2017 and provide these values in Table 2.[7] For easier comparison, the table also provides the WACC calculated for average 2017 interest rate levels alongside the markups. As indicated in the table, the coverage for many countries is still very limited; only for six countries are there values from three or more studies (OECD countries Denmark, Germany, and Greece; and non-OECD countries Brazil, India, and United Arab Emirates). The WACC levels for these countries are depicted in Fig. 8.

Clearly, the data points for different countries and technologies are drawn from studies which used different methods that each have limitations as discussed in Section 5. Nevertheless, the collective body of empirical evidence in Table 2 and Fig. 8 exhibits several patterns in how the cost of capital for RE projects differs between countries and technologies.

On average, the WACCs in developed countries are clearly below those for developing countries, with a difference between the average WACC between OECD and non-OECD countries of 2.0 percentage points for solar PV projects and 3.1 percentage points for onshore wind projects (see Fig. 8).[8] This pattern is consistent with the literature on RE

[7] Excluding pre-2009 values limits the analysis to the relatively stable interest rate environment mentioned above.

[8] Unweighted average of those OECD and non-OECD countries for which data are available. Offshore wind power has not yet been deployed at scale in developing countries.

Table 2
Average WACC markups and WACC at 2017 interest rates, per technology and country.

	Solar PV		Onshore wind		Offshore wind		No. of data points considered[a]
	$WACC_{after\text{-}tax}$ Markup to LIBOR	$WACC_{after\text{-}tax}$ at Ø 2017 LIBOR	$WACC_{after\text{-}tax}$ Markup to LIBOR	$WACC_{after\text{-}tax}$ at Ø 2017 LIBOR	$WACC_{after\text{-}tax}$ Markup to LIBOR	$WACC_{after\text{-}tax}$ at Ø 2017 LIBOR	(solar PV/wind ons./wind offs)
Austria			*L + 6.1%*	5.9%			(– / 1 / -)
Belgium	*L + 2.7%*	2.5%	*L + 3.5%*	3.3%	*5.7%*	5.5%	(1 / 2 / 2)
Brazil	*L + 4.6%*	6.4%					(3 / - / -)
Bulgaria			*L + 9.6%*	9.4%			(– / 1 / -)
Cambodia	*L + 8.6%*	10.4%					(1 / - / -)
Chile	*L + 3.1%*	4.9%					(2 / - / -)
China	*L + 5.6%*	7.4%					(1 / - / -)
Croatia			*L + 11.6%*	11.4%			(– / 1 / -)
Cyprus			*L + 9.6%*	9.4%			(– / 1 / -)
Czech Republic			*L + 7.6%*	7.4%			(– / 1 / -)
Denmark			*L + 5.2%*	5.1%	*L + 7.9%*	7.8%	(– / 3 / 1)
El Salvador	*L + 4.3%*	6.1%					(1 / - / -)
Estonia			*L + 9.3%*	9.1%			(– / 1 / -)
Finland			*L + 6.1%*	5.9%			(– / 1 / -)
France			*L + 5.3%*	5.1%			(– / 1 / -)
Germany	*L + 2.9%*	2.7%	*L + 3.1%*	3.0%	*L + 6.3%*	6.1%	(4 / 11 / 2)
Greece	*L + 12.0%*	11.8%	*L + 11.9%*	11.7%			(3 / 4 / -)
Guatemala	*L + 7.9%*	9.7%					(1 / - / -)
Hungary			*L + 10.9%*	10.7%			(– / 1 / -)
India	*L + 8.8%*	10.6%	*L + 9.6%*	11.4%			(5 / 3 / -)
Ireland			*L + 8.6%*	8.4%			(– / 1 / -)
Italy			*L + 7.6%*	7.4%			(– / 1 / -)
Jamaica	*L + 2.5%*	4.3%					(1 / - / -)
Jordan	*L + 3.7%*	5.5%					(1 / - / -)
Latvia			*L + 8.9%*	8.7%			(– / 1 / -)
Lithuania			*L + 8.1%*	7.9%			(– / 1 / -)
Malaysia	*L + 8.6%*	10.4%					(1 / - / -)
Mexico	*L + 3.1%*	4.9%					(1 / - / -)
Netherlands			*L + 5.9%*	5.7%	*L + 9.9%*	9.8%	(– / 1 / 1)
Peru	*L + 2.5%*	4.3%					(2 / - / -)
Poland			*L + 8.9%*	8.7%			(– / 1 / -)
Portugal			*L + 7.6%*	7.4%			(– / 1 / -)
Romania			*L + 10.7%*	10.5%			(– / 1 / -)
Saudi Arabia	*L + 2.5%*	4.2%					(1 / - / -)
Slovakia			*L + 7.7%*	7.5%			(– / 1 / -)
Slovenia			*L + 10.6%*	10.4%			(– / 1 / -)
South Africa	*L + 4.8%*	6.6%					(2 / - / -)
Spain			*L + 9.6%*	9.4%			(– / 1 / -)
Sweden			*L + 7.8%*	7.6%			(– / 1 / -)
Thailand	*L + 10.1%*	11.9%					(1 / - / -)
Uganda	*L + 6.0%*	7.8%					(1 / - / -)
United Arab Emirates	*L + 3.7%*	5.5%					(4 / - / -)
United Kingdom			*L + 5.5%*	6.2%	*L + 11.9%*	12.6%	(– / 1 / 1)
United States			*L + 4.8%*	6.5%			(– / 2 / -)
Vietnam	*L + 8.6%*	10.4%					(1 / - / -)
Zambia	*L + 2.5%*	4.2%					(1 / - / -)
Average OECD[b]	***L + 4.8%***	**5.4%**	***L + 7.4%***	**7.3%**	***L + 8.3%***	**8.3%**	
Average non-OECD[b]	***L + 5.6%***	**7.4%**	***L + 10.2%***	**10.4%**	–	–	

Notes: LIBOR = London Interbank Offered Rate (a common benchmark interest rate). As the EUR LIBOR was negative (−0.18%) in 2017, the WACC at Ø 2017 LIBOR rates is lower than the markup in EUR countries.
[a] Each study and year is considered as one data point, which might be based on several data points in the respective study.
[b] Unweighted averages of values from countries for which data area available.

investment in developing countries which emphasizes that high financing costs are an important barrier to investment (Schmidt, 2014; Shrimali et al., 2013). However, the difference between the average rate in OECD countries and the average rate in non-OECD countries for which data is available appears rather moderate, especially for solar PV with just 2.0 percentage points. Importantly, these averages compare rather heterogeneous groups of countries, as illustrated by Germany and Greece (both OECD), or India and the United Arab Emirates (both non-OECD)—underlining the necessity to consider the specific situation of each country.

For solar PV, since 2015 many large projects in developing countries have been deployed through competitive auctions that yielded a comparably low cost of capital (see the orange dots in Fig. 4), partly enabled by financial de-risking instruments from multilateral development banks. But there are large differences between developing countries: Jamaica, Peru, Saudi Arabia, and Zambia have a WACC for solar PV projects below 5%, and the WACC is above 10% for Cambodia, India, Malaysia, Thailand, and Vietnam. The data also show that for India (one of the largest solar PV markets) the WACC levels and markups hardly improved between 2011 and 2016, unlike in other countries.

For wind power projects, in contrast, no developing country has an estimated WACC below 5%, and the difference to OECD countries is larger, even though there are also several European Union (EU) countries with a WACC above 10% (Croatia, Greece, Hungary, Romania, and Slovenia).

Ordering the technologies by their cost of capital, we observe a clear pattern for all countries, with the WACC for solar PV projects the lowest,

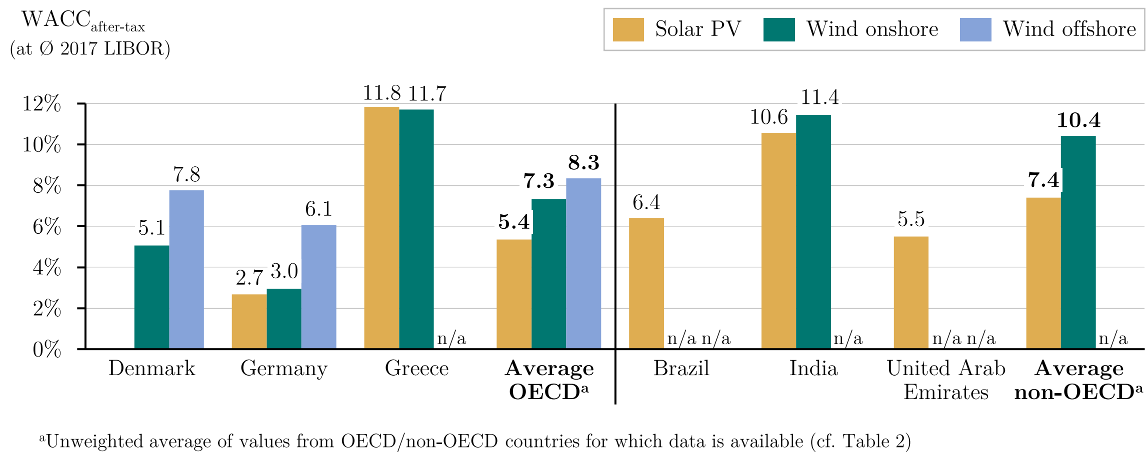

Fig. 8. Average WACC at 2017 interest rates.

followed by the WACC for onshore wind projects, and the WACC for offshore wind projects the highest.[9] This order reflects the investor perception that since having become fully mature, solar PV has a lower operational risk than wind (Egli et al., 2018), which also fueled the recent rapid expansion to developing countries (Steffen et al., 2018).

Finally, the cross-country variance showed in Table 2 is larger for onshore or offshore wind power than for solar PV, mainly driven by results from the broad interview-based studies by Angelopoulos et al. (Angelopoulos et al., 2016) and Voormolen et al. (Voormolen et al., 2016). Such a large variance is not apparent in the other broad studies by Wood & Ross (Wood and Ross, 2012) and Dobrotkova et al. (Dobrotkova et al., 2018) which, however, cover different countries. Thus, whether the different variance between technologies is due to actual technology differences or the estimation method used cannot be ascertained from the available data.

In sum, comparing the available empirical evidence shows differences between countries and technologies that are in line with expectations from qualitative literature, as discussed in Section 2.3. For many countries, empirical WACC estimates are now available, and can be used by energy economists and energy system modelers. However, the overall fragmented coverage, with many countries having been investigated in only one or two articles, clearly calls for further research to increase the reliability of the estimates.

7. Conclusion

Aiming to address the scarcity of solid data on the cost of capital for RE projects, this systematic literature review identified 19 articles that estimated WACCs for solar PV, onshore wind, or offshore wind power, yielding values for 46 countries. For these countries, we find a consistent rank order among technologies, with the cost of capital increasing from solar PV to onshore wind to offshore wind power. On average, the cost of capital in developing countries is significantly higher than in industrialized countries, but major differences also occur between countries which are comparable with respect to their state of economic development.

The suitability and limitations of different estimation methods has been discussed, suggesting that future research on RE cost of capital can further improve the accuracy of the estimates by taking into account all the refinements that extant literature has proposed. Concerning the empirical scope of future studies, some major gaps in coverage should be addressed. For instance, data for major RE markets, such as France, Italy, and the United States, are very limited. In addition, it would also be desirable to gather additional evidence on countries for which estimates are already available, because only a regional overlap of studies will allow to more profoundly assess the consistency of studies (i.e. several studies need to estimate values for the same countries to allow a comparison of results). Increased country and technology overlap can help improve understanding of the uncertainty in results for a particular method, such as expert estimates (cf. Nemet et al., 2017), and compare the precision delivered by different methods.

For energy economists, and energy system modelers more generally, the large heterogeneity in WACC estimates that became apparent in this article clearly emphasizes the relevance of using different cost of capital assumptions in many contexts. The present analysis yielded robust evidence for differences between countries and technologies that can be used, for instance, in RE investment models and energy system models with endogenous investment.

Finally, the transparency that this review created should also be of interest to policymakers concerned about decarbonizing power generation. The large differences in the cost of capital for RE projects between countries highlights not only the need to consider RE cost of capital for cost-effective deployment strategies (cf. May and Neuhoff, 2017), but also the potential to explicitly address financing costs as part of a renewable energy policy mix (Geddes et al., 2018; Kirkpatrick and Bennear, 2014; Krupa et al., 2019; Shrimali et al., 2013). In the European Union, for instance, policymakers acknowledge that reducing financing costs can have a material impact on the competitiveness of RE (EU Commission, 2018), but only transparency of cost of capital across countries and technologies will allow to design appropriate policy interventions.

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Author statement

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Declaration of Competing Interest

The author declares no competing interests.

[9] The only exception is Greece where the WACCs for solar PV and onshore wind power are almost identical at 11.8% and 11.7%, respectively.

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Appendix A. List of abbreviations

Table A.1
Abbreviations used in the article.

Abbreviation	Explanation
BNEF	Bloomberg New Energy Finance (a financial data provider)
CDS	Credit default spread
CoD	Cost of debt
CoE	Cost of equity
DS	Debt share
EU	European Union
IEA	International Energy Agency (an international organization)
LIBOR	London Interbank Offered Rate (a benchmark interest rate)
LCOE	Levelized cost of electricity
PV	Photovoltaics
OECD	Organization for Economic Co-operation and Development
PPA	Power purchase agreement
RE	Renewable energy
RQ	Research question
SPV	Special purpose vehicle
WACC	Weighted average cost of capital

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2020.104783.

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