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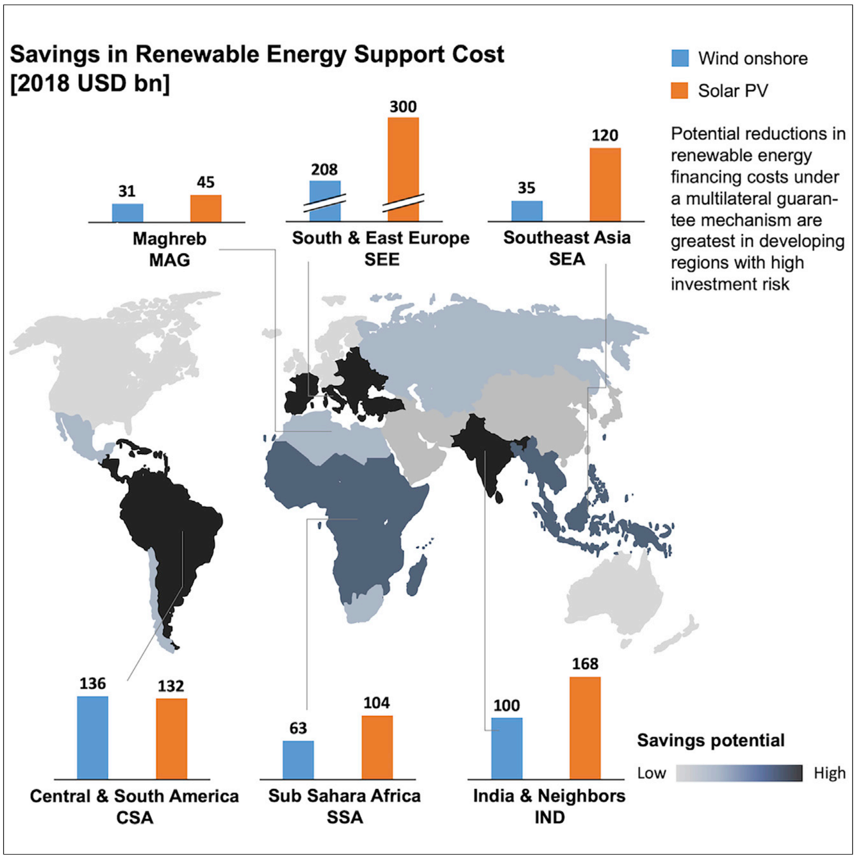

In many parts of the world, adverse financing conditions are a significant barrier to necessary investments in renewable energy. A global guarantee mechanism can mitigate real or perceived investment risks, which increase the cost of financing renewable energy projects. Cost savings from such a mechanism could be substantial, reaching $1.5 trillion globally by 2030. By scaling up existing bi- and multilateral risk guarantees, the international community could help accelerate energy system decarbonization in less-affluent regions at a reduced cost.

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HIGHLIGHTS

A global guarantee mechanism can reduce the cost of renewable energy investments

It can be established by scaling up existing bi- and multilateral risk guarantees

Potential savings are substantial and could reach $1.5 trillion globally by 2030

Savings at this scale can help accelerate decarbonization in the developing world

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Article

De-risking Renewable Energy Investments in Developing Countries: A Multilateral Guarantee Mechanism

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SUMMARY

Mitigation of global warming requires substantial investment in electricity generation from renewable sources. A large share of new generation capacity is required in regions with adverse financing conditions. We propose a global guarantee mechanism to reduce risk premia of renewable energy investments by means of risk pooling and increased market efficiency. Policymakers could establish this mechanism by scaling up existing international risk guarantee initiatives. We estimate the net present value of overall savings at US$$_{2018}$ 1.5 trillion globally for investments by 2030, with the largest relative savings (between 20.5% and 22%) in Sub-Saharan Africa and the Maghreb. The savings from such a mechanism outweigh its estimated average yearly operating cost. By lowering the cost of decarbonization in high-risk countries, the proposed mechanism offers policymakers a tool to make current global mitigation pledges more achievable and enables the global community to pursue more ambitious climate action.

Context & Scale

In many parts of the world, adverse financing conditions are a significant barrier to necessary investments in renewable energy. Real and perceived investment risks, in particular, increase the cost of financing renewable energy projects. A global guarantee mechanism can lower such risks, thereby reducing the cost of deploying renewable energy. We estimate the cost savings from such a mechanism to be substantial, reaching up to $1.5 trillion globally by 2030. In some regions, the cost of renewable electricity generated could be lowered by up to $31 per MWh. At relatively moderate cost, multilateral development banks and other financial institutions could establish a guarantee mechanism that builds on existing risk guarantees and helps accelerate energy system decarbonization in less-affluent regions. That, in turn, would improve the prospects of achieving temperature stabilization targets agreed under the Paris Agreement with currently available technologies.

INTRODUCTION

Averting the most serious impacts of climate change will require concerted action at an unprecedented scale. Current efforts pledged in the Paris Agreement are inadequate to achieve the 2°C temperature stabilization objective, much less the more ambitious 1.5°C objective.[1,2] Consequently, climate projections increasingly feature temperature or carbon overshoot scenarios[3–5] and rely on negative emission technologies such as bioenergy with carbon capture and storage.[6–8] However, these technologies are still untested at scale and, hence, pose uncertain technological and economic challenges (e.g., Fuss et al.,[9] Smith et al.,[10] and Rogelj et al.[11]).

Instead of betting on uncertain technological progress, governments can focus on a rapid expansion of carbon-neutral electricity supply using existing renewable energy technologies. In this article, we, therefore, focus on electricity generated from renewable sources such as wind and solar power. If other sectors—such as transportation and industry—decarbonize through partial or full electrification, the necessity of rapid expansion scenarios (e.g., Jacobson et al.[12,13] and Ram et al.,[14]) with 80% (100%) carbon-free electricity by 2030 (2050) increases. These aggressive expansion scenarios require substantial investment in all parts of the world, amounting to about US$$_{2018}$ 60 to 120 trillion between 2015 and 2050 in developed economies and in developing countries with adverse financing conditions.[12,15]

A large share of the required investments depends on the financing conditions, which exhibit a large regional disparity for renewable energy projects.[16] Recent studies confirmed a major impact of financing conditions such as investors' risk premia on the cost of electricity, particularly for renewable energy investments, (e.g., Schmidt,[17] Egli et al.,[18] and Steffen[19]) and analyzed relevant drivers of risk (e.g., Schmidt et al.[20] and Polzin et al.[21]). One of the main risks for investors is that of default on (governmental) power-purchase agreements or failure to disburse feed-in tariffs.[21]

In this article, we explore how this major investment barrier can be addressed with a guarantee mechanism for the remuneration of electricity generation from renewable energy projects. A guarantee mechanism for renewable energy payments can reduce the cost of decarbonization in the electricity sector of high-risk countries by pooling risk from different countries and increasing market efficiency. By lowering the cost of decarbonization in high-risk countries, the proposed mechanism offers policymakers a tool to make current mitigation pledges more achievable, enable the global community to attenuate serious economic consequences of climate change (e.g., Hanewinkel[22] and Hsiang[23]), and support sustainable recovery efforts in the wake of the coronavirus disease 2019 (COVID-19) crisis, which foresee large investments in clean energy technologies.[24]

Investment guarantees for renewable energy are not a new idea. Our contribution to the literature consists of describing how a guarantee mechanism for remuneration contracts of renewable energy projects could be operationalized at the global level and of quantifying the potential savings it could yield in an aggressive expansion scenario, assuming that all contracts for remuneration are provided via auctions for support of electricity generation from renewable sources.

We find that the net present value of savings in a 10-year scenario amounts to US$$_{2018}$ 1.5 trillion with the largest absolute savings in Central and South America, India and neighboring countries, as well as South and East Europe, followed by Sub-Saharan Africa and Southeast Asia. The largest relative savings (between 20.5% and 22% of originally expected remuneration) can be attained on the African continent in Sub-Saharan Africa and the Maghreb, respectively. Expressed in terms of levelized cost of electricity (LCOE), reductions of up to 31 US$$_{2018}$/MWh can be delivered in some regions. The guarantee facility could be financed by a multilateral alliance of donor countries and by a participation fee collected from investors that is based on the amount of generated electricity. We estimate that funding requirements amount to a yearly average of US$$_{2018}$ 29 billion until 2055 (we consider renewable energy investments between 2020 and 2030 with a guaranteed remuneration period of 25 years. Therefore, we provide cost _gures until 2055), which is in the range of current public finance for renewable energy investments.

Our study builds on a policy mechanism conceptualized and proposed for the European Union[25–27] and describes the introduction of such a mechanism at the global level. We endogenize capacity expansion, investor interaction, and financing conditions, among others, in our simulations of renewable energy support policies. This allows us to assess resulting remuneration in the prevalent setting of auctions for support of electricity generation from renewable sources.[28,29]

For our renewable energy expansion scenario, we draw on high-resolution analysis of a global electricity system relying on 100% renewable energy sources that was published earlier in this journal.[12] By lowering the cost of capital for renewable energy investments and inducing at least partial convergence across countries, a multilateral guarantee mechanism would help mitigate one of the main critiques leveled

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against such scenarios—insufficient reflection of the heterogeneity of real-world cost of capital[30]—while increasing overall economic efficiency.

The remainder of this paper is organized as follows. In A Multilateral Guarantee Mechanism for Renewable Energy, we discuss relevance, mandate, and structure of a guarantee mechanism at the global level. In Model Framework, we provide an overview of our simulation model, which we detail in the Methods. We present our results in Reduction in Financing Cost: Global Results. Conclusion and Policy Implications concludes and provides policy implications.

A Multilateral Guarantee Mechanism for Renewable Energy

Several converging trends are prompting countries around the world to scale up their investments in renewable energy. With rapidly falling technology costs, renewable energy sources offer an increasingly competitive alternative to traditional sources for countries looking to meet energy demands, expanding electricity access, and reducing their reliance on imported fuels. Under the Paris Agreement, these same countries have committed to deep decarbonization by the second half of the century. This commitment is being implemented in a growing number of national and subnational jurisdictions through renewable energy deployment targets and support policies, aiming to drive investment in clean energy technologies and infrastructure e.g., IRENA.[31,32]

Compared to conventional energy sources, whose costs are primarily determined by the cost of fuels, renewable energy technologies tend to be significantly more capital intensive, with a high initial capital expenditure (e.g., Egli et al.[18] and Hirth and Steckel[33]). This capital intensity comprises the (upfront) investment cost—including the technology as such, but also land, construction, and project development costs—as well as financing costs. Given the decline in technology costs as well as operational improvements in construction and project development, financing costs have become the primary cost determinant for renewable sources.[34] This sensitivity in financing costs dramatically affects the competitiveness of renewable energy technologies and alters the marginal abatement cost of reducing greenhouse gas emissions.[17]

Financing costs for renewable energy investments depend on a number of factors, such as the cost of debt, the required return on equity, the debt to equity ratio, the period for which debt and equity need to be committed, and fees paid for acquiring the required capital.[35] The risk of investment directly affects the cost of capital, since it causes lenders to raise the cost of debt through higher interest rates and equity investors to raise the cost of equity through higher return expectations.[36] Some sources of public finance—such as sovereign and multilateral lenders—are often less sensitive to risk, but the massive scale of investment needed to decarbonize the global energy system cannot be met with public funds alone.[37] In recent years, public funds have played a growing role in stabilizing renewable energy investment volumes over time,[38] underscoring the importance of public intervention to unlock private capital and mobilize the required levels of private investment.

Investment decisions in the private sector are based on the risk-return profile of investment opportunities.[36] Policymakers can, thus, lower financing cost by lowering the associated risks.[21] This is particularly relevant for developing countries, where much of the future energy sector investment will be needed, but informational, technical, regulatory, administrative, political, and financial barriers contribute to a higher perception of risk. Project developers in such countries therefore often struggle to access financing and—where available—can only secure it at a substantially higher cost than in developed countries.[34]

Risk in renewable energy investments can take multiple forms, including technology or resource risk, grid and transmission link risk, currency, liquidity and refinancing risk, political and regulatory risk, as well as counterparty risk.[39] For policymakers, this offers multiple levers to lower renewable energy financing costs and cost of greenhouse gas abatement by de-risking such investments.[17] An effective way to de-risk renewable energy projects in the electricity sector is to address one of the major risks perceived by investors: the default of the power off-taker.[21] To this end, policymakers can transfer some or all of the resulting negative financial impact to a (multilateral) guarantee mechanism.[34] Studies have shown that guarantees reduce the risk for investors and, thus, accelerate the deployment of and investment in renewable energy.[21]

Guarantees are usually issued by public entities, such as governments and international financial institutions, and allow a limited amount of public funds to leverage multiples in private capital. In the context of renewable energy investments, for instance, public entities could backstop risks associated with renewable energy projects and ensure that the investors receive the guaranteed remuneration for electricity generated by the project in the event a covered risk materializes. In return, investors pay a participation fee that helps defray some or all of the operating and maintenance costs of the guarantee. Guarantee mechanisms, thus, contribute to a more efficient market for risk by offering a risk pooling, thereby creating a benefit for all market actors.[40] Overall, a guarantee mechanism helps to overcome market frictions, enabling renewable energy projects that were previously infeasible economically.

The disparity of risk perception is already large when considering the European Union. In 2016, Temperton et al.[25] outlined a conceptual proposal and roadmap for a guarantee facility to insure remuneration of renewable electricity projects in the European Union, the Renewable Energy Cost Reduction Facility (RE-CRF). The study proposes a voluntary contractual mechanism to help lower the cost of capital for renewable energy investments across Europe. The participating Member States would enter into a contract with a creditworthy institution at the European level, i.e., the RE-CRF, which in turn would (under certain conditions) provide investors with a guarantee for remuneration promised by the Member State, i.e., eligible investors continue to receive remuneration for their protected projects from the RE-CRF if the corresponding Member State defaults to pay the remuneration.

The RE-CRF would be financed from three sources. First, Member States would provide a share of the financing needed to set up the facility and it would be primarily financed from the European Union budget. Second, participating investors would be charged a fee of 1 €/MWh to cover the operating expenses of the facility and contribute to its maintenance. Third, beneficiary Member States would commit to (later on) repaying any payments made to investors under the facility in case the guarantee is drawn. Agora Energiewende[26] has estimated that such a RE-CRF could lower the economic dead-weight cost of achieving the 2030 renewable electricity deployment target by approximately € 34 billion (approx. US$ 38 billion), making the market for risk more efficient, comparable to an insurance company.

Given the even greater heterogeneity of country risk profiles and financing costs beyond Europe, a similar guarantee mechanism deployed at the global level could yield significantly larger savings. We estimate these potential savings in the remainder of this paper (Model Framework, Reduction in Financing Cost: Global Results, and Conclusion and Policy Implications).

The institutional setup of a guarantee mechanism at a global level would necessarily differ. Whereas the proposed European RE-CRF could draw on existing governance and budgetary structures of the European Union, an international guarantee mechanism would require multilateral cooperation to establish suitable institutional and policy frameworks. It would not have to start from scratch, however. With its aim to improve the availability of renewable energy finance and, thereby, accelerate access to sustainable electricity, an international guarantee facility could fall within the institutional mandate of existing organizations, in particular multilateral finance institutions such as the World Bank Group and regional development banks. Such institutions already provide guarantees at smaller scales, for instance, through the Multilateral Investment Guarantee Agency.

Only about 4%—or equivalently US$ 1.8 billion—of overall US$ 43.1 billion in climate finance issued by multilateral development banks in 2018 was allocated to guarantees.[41] Increasing these guarantees has been described as "relatively simple in terms of policy and execution," as it would only require scaling up existing capabilities and adopting limited policy changes.[42] Still, the mobilization of funds to operationalize an international guarantee mechanism for investments in electricity from renewable sources would not be trivial (A suitable governance framework would require the buy-in of participating countries. But even if a gradual introduction with an initial coalition of a limited number of like-minded countries is more feasible, the ability of the guarantee mechanism to mobilize greater investment flows would likely attract growing participation over time.). A significant share of the required funds would come from the participation fee paid by investors, which we propose to set at US$$_{2018}$ 1 for each MWh covered under the mechanism. This still leaves a capitalization gap, however, which we discuss further below.

Determining the capital requirement of a guarantee mechanism requires an assessment of the likelihood and frequency of the guarantee being drawn due to default of renewable electricity remuneration arrangements in participating jurisdictions. In this article, we merely provide a first heuristic estimate. Given the central role of governments in ensuring the remuneration of renewable electricity projects—either because they are themselves the power off-takers or because they are liable for enforcing support policies such as feed-in tariffs—sovereign default rates can serve as an initial proxy of default risk (we acknowledge that sovereign default rates are a lower bound to default risk as governments might prioritize other liabilities over renewable electricity) remuneration. Yet, sovereign default rates can serve as a baseline and are frequently used to determine default risk in renewable electricity projects as it is a key driver of the creditworthiness of a project.[43]

According to Standard & Poor's 2018 Global Rating, the sovereign local currency average default rate across all rated countries between 1993 to 2018, based on the number of issuers defaulting on sovereign debt, was 0.58% in one year and 6.80% cumulatively over 15 years.[44] Additionally, a recent evaluation of sovereign debt restructurings over the last two centuries has shown that full repudiation is rare, with a median recovery rate after default in excess of 50%.[45] In the scenario we assume in this paper of full power sector decarbonization by 2050, even a conservative assumption (accounting for lemon markets, among others) that 1.5% of remuneration arrangements in any given year will experience default suggests a

Table 1. Regional Clustering of Simulation Study

Continents	Regions	Code	Representative	Code
Africa	Maghreb	MAG	Egypt	EGY
	South Africa	ZAF	South Africa	ZAF
	Sub-Saharan Africa	SSA	Nigeria	NGA
Asia	China and Neighbors	CHN	China	CHN
	Central and North Asia	CNA	Russia	RUS
	Middle East and Arabia	MEA	Qatar	QAT
	India and Neighbors	IND	India	IND
	Southeast Asia	SEA	Indonesia	IDN
Australia	Australia and New Zealand	ANZ	Australia	AUS
Central and South America	Central and South America	CSA	Brazil	BRA
Europe	Central and North Europe	CNE	Germany	GER
	South and East Europe	SEE	Italy	ITA
North America	North America	NAM	USA	USA
North/South America	Chile and Mexico	CME	Chile	CHL

We cluster countries into regions with comparable economic outlooks and macroeconomic data. For each cluster, we select a representative country.

maximum amount of US$$_{2018}$ 3.3 billion is at risk in the first year, growing to a maximum of US$$_{2018}$ 40 billion at risk by 2030 (These figures are calculated assuming that all countries included in our model [see Table 1] participate in the guarantee mechanism. Also, we assume a project lifetime of 25 years and consider investments between 2020 and 2030. Accordingly, the amount at risk grows from 2020 until 2030 with an increasing number of projects, stays on its maximum between 2030 and 2040, and declines from 2040 until 2055 due to projects rotating out of the guarantee mechanism.). As mentioned earlier, the vast majority of this funding requirement would be offset by the participation fee of US$$_{2018}$ 1 for each MWh covered under the mechanism: fees add up to US$$_{2018}$ 3.2 billion in the first year and US$$_{2018}$ 39 billion by 2030.

The remaining gap could be funded by a coalition of multilateral and regional development banks as well as individual donor countries. The required amount is not outright unrealistic when compared to current annual flows of public investment in renewable energies of US$ 54 billion.[46] Furthermore, existing guarantee mechanisms (These may include risk guarantees of development _nance institutions or export credit agencies, guarantees by national or subnational government agencies, and central bank or state-level bank guarantees, among others.[43]) already dedicated to securing renewable energy investments could be counted toward this amount. In all cases, the savings we estimate below from lower financing costs under a guarantee mechanism fully outweigh the funding requirements.

To further attenuate the funding requirements of donor countries, in the long run, the opportunity of countries to participate in the guarantee mechanism could be made contingent on an indemnity agreement. Similar to the European RE-CRF, countries would formally pledge to reimburse any guarantees drawn from the mechanism in the event of default. Depending on its institutional mandate, the mechanism itself could seek recovery when countries renege on their pledge. Delayed reimbursement could be subject to penalty interest to dissuade defaulting countries from holding back repayment. Countries in default that altogether refuse to honor their reimbursement pledge would lose access to the guarantee mechanism, creating a strong incentive to play by the rules.

In some cases, holding the defaulting countries liable for recovery may not be equitable, however, especially in the case of low-income countries already faced with budgetary and other socioeconomic constraints or in the event of external systemic shocks such as a financial crisis. As investments in renewable energy projects also generate profits that accrue at least in part to high-income countries; moreover, such lenience would not be purely altruistic. Alternative recovery models could rely on a higher participation fee by investors, which will typically originate from high-income countries or creation of a hardship fund by donors to indemnify defaulting countries on a case-by-case basis. The substantial funds held in reserve for the contingency of a default could also be reinvested in readily marketable, low-risk securities to generate interest that can help cover such contingencies or be used to build human and technical capacity in countries so as to enable their participation in the guarantee mechanism.

Overall, thus, the multilateral guarantee mechanism would bear structural similarities to the RE-CRF proposed for a European context, including the reliance on participation fees and on a public source of funding to fill the capitalization gap. However, it would also have to reflect vastly different national circumstances at the global level, which would potentially necessitate a different recovery mechanism as well as other modifications from the European context. Existing entities, such as the Green Climate Fund, have shown that the establishment and governance of multilateral institutions is a complex and highly political exercise. In any event, the creation of a multilateral guarantee mechanism would necessarily be preceded by extensive negotiations to secure consensus across parties and to make the outcome mutually acceptable. The broad parameters we have outlined here are but a tentative first effort to envision how such an entity could be designed.

In Figure 1, we visualize the structure of this potential design and the relationships of actors involved in operationalizing it, summarizing the discussion of the previous paragraphs. With funding in the magnitude of current international flows of finance into renewable energies, donor countries could establish a guarantee facility, pooling the risk of default and providing a more efficient market for renewable electricity projects around the world.

In the future, such a guarantee mechanism could transform into a lending or grant-making facility once a certain penetration of renewable electricity has been achieved globally, relying on the—by-then established—structure. In the following section, we describe essentials of our model framework, which we use to simulate savings initiated by the guarantee mechanism. We substantiate the model in Conclusion and Policy Implications.

Model Framework

We combine an aggressive scenario of renewable capacity expansion and a framework of auctions for renewable electricity support to estimate the financial impact of the guarantee mechanism for remuneration contracts of renewable electricity projects. Starting from the roadmap for capacity expansion, we model auctions for support of electricity generated from renewable sources in 14 key countries in a setting with and without a guarantee mechanism. As discussed in the previous section, the introduction of a guarantee mechanism reduces investor risk premia. This reduction

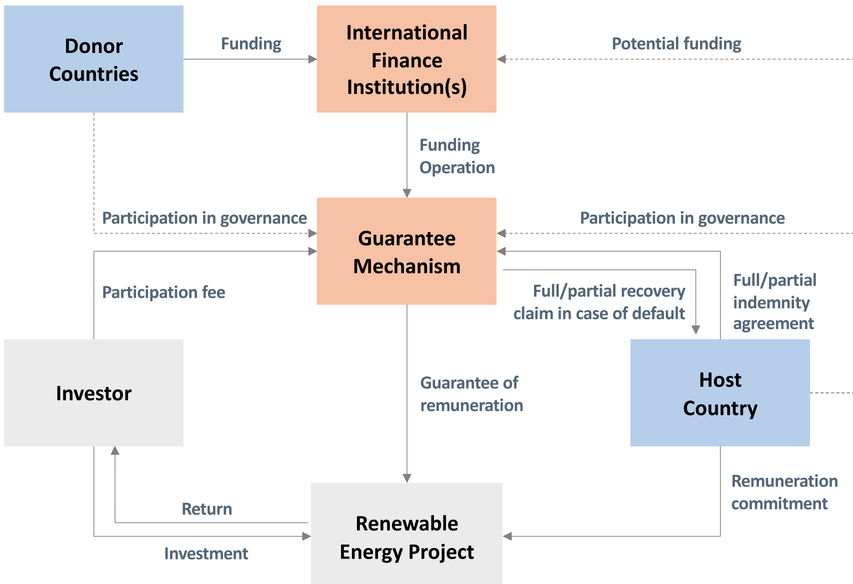

Figure 1. Structure of a Potential Guarantee Mechanism

Structural arrangements, dependencies, relationships, and responsibilities of a potential guarantee mechanism. Country-level stakeholders are depicted in blue, international agencies in orange, and project level stakeholders in gray.

is reflected in the financing cost, which in turn affects bidding behavior in auctions for renewable electricity support.

We assume an expansion pathway proposed by Jacobson et al.[12,13] It leads to a fully renewable energy system by 2050, meaning that all electricity generation is renewable, and other areas such as transportation and residential heating have been electrified. The pathway proposed by Jacobson et al.[13] and his previous work has been discussed controversially in the literature (e.g., Clack et al.[47]). It assumes a comparably aggressive expansion to 100% renewable electricity with a very high penetration of renewables. With the projected investment of US$$_{2015}$ 124.7 trillion until 2050 (i.e., US$$_{2015}$ 3.5 trillion per year), it lies slightly above the model average of about US$$_{2015}$ 3.2 trillion reported by McCollum et al.[48] But, other 1.5°C pathways discussed in McCollum et al.[48] estimate capital expenditures similar to or above Jacobson et al. (cf.,[13] Fujimori et al.,[49] Kriegler et al.,[50] Luderer et al.[51]). Jacobson et al.[12] proposes a total production capacity of 52 TW with a global final energy demand of 373 EJ per year in 2050, which is on the lower end of comparable projections cf.[52] Grubler et al. We extract from Jacobson et al.[12] capacity additions of 139 countries until 2020, 2025, and 2030 from Jacobson et al.[13] and interpolate capacity additions for single years.

Roadmaps for 100% renewable energy supply increasingly rely on auctions for renewable electricity support and over 90 governments have shifted their current support mechanism to auctions e.g., Ram et al.[14] and IRENA[28] Therefore, we assume that the capacity additions will be entirely managed with this support instrument (A staggering amount of 97.5 GW of renewable capacity was auctioned from 2017 to 2018, equaling about 20% of worldwide capacity additions in solar and wind during the same period.[28,53] With more and more countries shifting their policy framework to auctions, this share will further increase in the future.[28]), and we calculate remuneration accordingly. For our model, we assume one auction per country and year, this is an abstraction from reality, where multiple auctions (typically about 4) are held per country. By adjusting bidder numbers per auction, our results are robust to this simplification.

We follow Matthäus et al.[54] in their approach and weave real options theory into the bidding behavior of participants. Contradicting conventional wisdom and modeling, bidders do not bid under the assumption of certain delivery of the project. Instead, they perceive the project as a real option, similar to a financial put option. This means that they acquire the right, but not the obligation, to develop a renewable energy project and bear the option of non-realization in mind. This lowers demanded support levels drastically. We adapt the empirically validated model to 14 model countries (see Table 1). Based on these country-level results, we estimate a corridor of savings on a regional and worldwide level.

Even though the guarantee mechanism would not address major political or inflation-related risks, it would cover the possibility of default on power-purchase agreements or feed-in tariffs, as discussed previously. A reliable power-purchase agreement or tariff scheme profoundly affects the risk assessment performed by project developers. Their risk calculation after utilizing their real option to build is reflected in their cost of debt (CoD) and cost of equity (CoE),[17,34] which are pooled in the weighted average cost of capital (WACC) (Note that investors use the WACC to calculate project risk under the assumption of realization, i.e., after resolving the uncertainty of the real option. Therefore, WACC and real option do not account for the same uncertainties.) The WACC has a substantial impact on the financing costs of renewable energy projects[18,20] and, consequently, influences bids in renewable electricity support auctions. We assume WACC on a country-level and use financial data provided by Damodaran[55] to identify the respective CoD and CoE. We then run our simulation for two scenarios—with and without a guarantee mechanism—and reduce the CoD and CoE to reflect the lower risk of default in the former scenario. Drawing on the study by Agora Energiewende,[26] we assume a participation fee of 1 US$$_{2018}$/MWh to benefit from the guarantee mechanism.

With the capacity expansion, auction framework, and risk premium as given parameters, we simulate outcomes of auctions for renewable electricity support. We conduct a Monte Carlo simulation with 100 samples for each country, technology, and year to account for idiosyncratic sampling bias in our computational model. Simulations are performed with MATLAB R2019a. Below, we use average values from the Monte Carlo sample, and discount support payments to 2020 to permit comparison between countries.

Reduction in Financing Cost: Global Results

The proposed guarantee mechanism could yield substantial benefits for large parts of the world, see Figure 2. Based on our simulation of 14 regions, the net present value of cumulative savings in the nine benefiting regions (CNA, CSA, IND, MAG, SEA, SEE, SSA, ZAF, and CME) amounts to US$$_{2018}$ 1,547 billion in 2020 (including participation fee). This figure is equivalent to 7.2% of the cumulative GDP2018 of these regions, according to World Bank Data (https://data.worldbank.org, Indicator NY.GDP.MKTP.CD) and falls somewhere between the GDP$_{2018}$ of Australia and the Republic of Korea. For two regions (CHN and MEA), the expected participation cost outweighs the expected savings, while the remaining three regions (AUS, CNE, and NAM) do not profit from a guarantee mechanism due to high existing trust levels of investors. Our findings remain valid in the event of rising or declining general

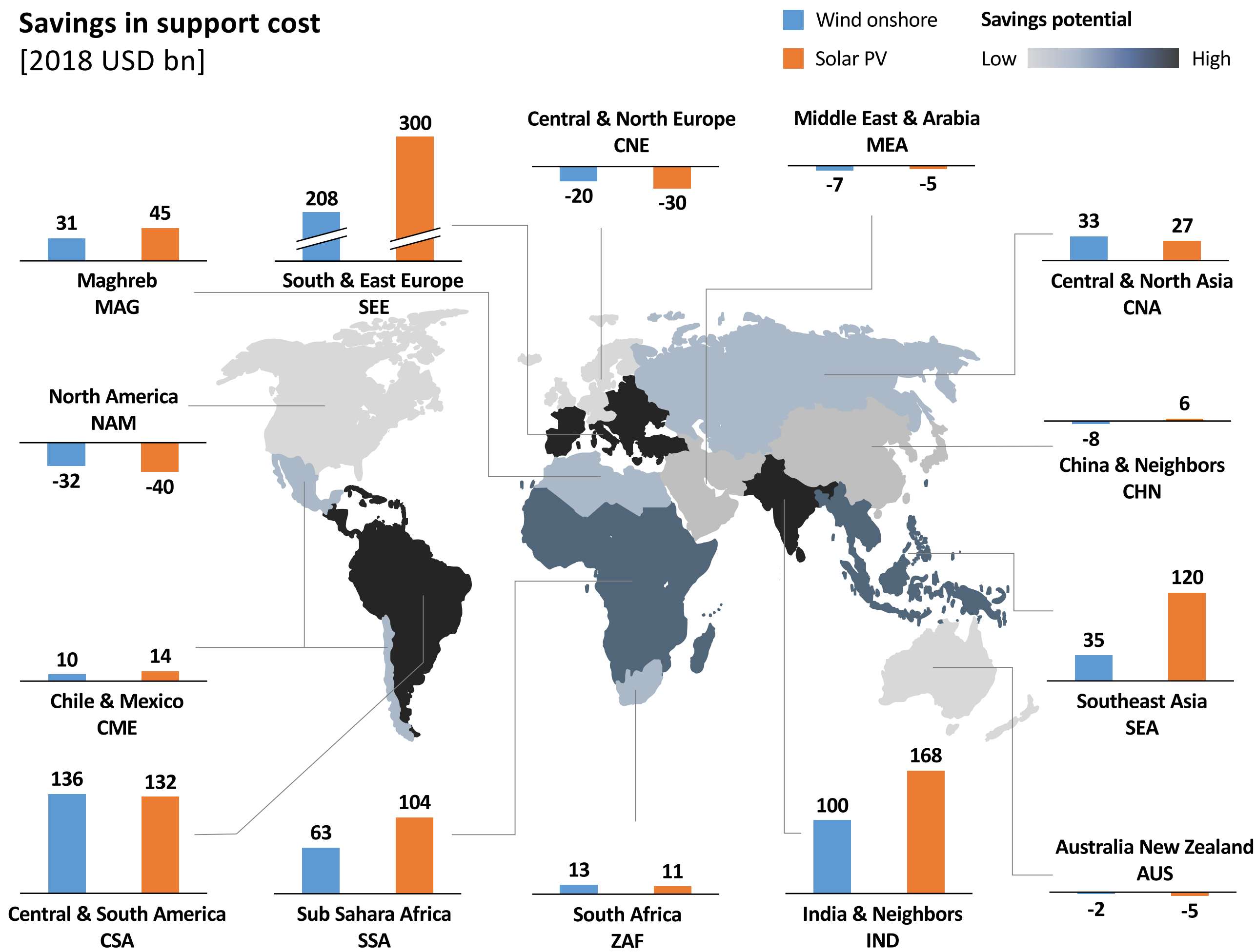

Figure 2. Net Present Values of Regional Savings

Net present values of savings induced by a guarantee mechanism, including the participation fee of 1 US$$_{2018}$/MWh. We report savings in contracts issued between 2020 and 2030 in US$$_{2018}$ billion. Nine regions profit substantially (CNA, CSA, IND, MAG, SEA, SEE, SSA, ZAF, and CME), while for the remaining five regions (AUS, CHN, CNE, MEA, and NAM) participation cost outweighs the reduction of risk premia or no risk reduction takes place due to initial high trust of investors.

interest rates. We leverage the effect of added country risk, which is independent of the base rate (see Conclusion and Policy Implications).

We present the results per region in Table 2. SEE realizes the largest absolute savings (about US$$_{2018}$ 500 billion), which results from a comparably large expansion of capacities and a substantial reduction in capital costs. The largest relative savings (between 20.5% and 22% of originally expected remuneration) can be attained on the African continent in SSA and MAG, respectively. This substantial gain stems from high reductions in the cost of capital of about 6 and 7 percentage points, respectively. When measuring savings in terms of GDP, SSA and MAG profit most. The savings amount to 16.2% and 14.6% of their GDP in 2018, respectively. In CSA, the comparably large share of capital costs in the LCOE allows for a pronounced effect of the guarantee mechanism, with an expected reduction in LCOE of 26 US$$_{2018}$/MWh. Changes in LCOE illustrate the effect of a guarantee mechanism in regions which do not profit from a guarantee mechanism. In CHN and MEA, the

Table 2. Simulation Results for Savings in Remuneration on Regional Level

	Savings Remuneration							Reduction LCOE		
	[Billion US$$_{2018}$]			[% Remuneration]			[% GDP]	[US$$_{2018}$/MWh]		
	Wind	Solar	Total	Wind	Solar	Total	Total	Wind	Solar	Total
AUS	−2.3	−4.8	−7.1	−1.4	−1.7	−1.6	−0.4	−1	−1	−1
CHN	−8.4	6.3	−2.1	−0.7	0.2	−0.1	0.0	0	0	0
CME	9.5	13.5	23.0	3.9	3.4	3.6	1.5	7	2	3
CNA	33.4	26.8	60.2	9.6	12.0	10.6	3.1	3	5	4
CNE	−20.1	−29.6	−49.7	−1.6	−1.2	−1.4	−0.3	−1	−1	−1
CSA	135.6	132.1	267.7	14.1	14.3	14.2	8.5	53	17	26
IND	100.2	167.8	268.0	8.8	9.8	9.4	8.5	7	7	7
MAG	30.5	44.5	74.9	21.4	22.4	22.0	14.6	39	27	31
MEA	−6.5	−4.5	−11.0	−2.0	−0.9	−1.3	−0.4	0	0	0
NAM	−31.5	−39.7	−71.2	−1.6	−1.6	−1.6	−0.3	−1	−1	−1
SEA	34.8	120.4	155.2	10.4	10.1	10.2	4.8	29	8	9
SEE	207.6	299.6	507.2	12.2	14.4	13.4	7.6	11	16	13
SSA	63.1	104.3	167.4	19.9	20.9	20.5	16.2	32	22	25
ZAF	12.8	10.8	23.6	9.9	10.7	10.2	6.4	8	6	7

We report absolute savings in billion US$$_{2018}$, relative savings in the percentage of initial expected remuneration and the percentage of the GDP$_{2018}$ of the region, and savings in LCOE in US$$_{2018}$/MWh. All numbers include participation fees.

net effect in terms of LCOE reduction is 0 US$$_{2018}$/MWh. In other words, the participation fee of 1 US$$_{2018}$/MWh outweighs the savings. AUS, CNE, and NAM would suffer from the participation fee without experiencing a reduction in risk premia. This increases the LCOE by 1 US$$_{2018}$/MWh. Thus, countries from AUS, CNE, and NAM would not participate as host countries but still be involved as donor countries in the mechanism.

Factoring in our more aggressive renewable electricity expansion scenario, these results are comparable in magnitude to findings of Agora Energiewende.[26] The authors propose a reduction of financing cost of approximately US$$_{2018}$ 40 billion (€ 34 billion) in the European Union and US$$_{2018}$ 12 billion (€ 10 billion) in the Southeast European Member States. Their scenarios are based on the European Union policy objective for 2030, which aims for a share of at least 32% of renewable energy (across all energy sources), while our scenario aims for a share of 80% of renewable electricity by 2030, in line with ambitious decarbonization targets. Also, our definition of SEE includes Belarus, Turkey, and Ukraine, which are not members of the European Union but account for a considerable share of overall capacity expansion in the region.

Conclusion and Policy Implications

Different pathways exist to achieve the goal of carbon neutrality, pledged by the international community under the Paris Agreement and increasingly also contained in binding national and subnational legislation. Regardless of the path that is ultimately taken, substantial amounts of investment in renewable energy will be required. Financing conditions and de-risking of investment projects play a critical role in the achievement of carbon neutrality. Governments have the opportunity to lower some of the economic dead-weight cost of mitigating climate change through the coordinated introduction of a guarantee mechanism at the global level.

While a global guarantee mechanism has the potential to reduce large amounts of dead-weight cost and thereby speed up the pace of decarbonization, its roll out on a global level will prove a political challenge. If successfully implemented, a guarantee mechanism at the global level can unlock remarkable savings in the investment necessary to fight climate change. We have quantified the net present value of potential savings for renewable electricity support as exceeding US$$_{2018}$ 1 trillion, distributed across the globe (cf. Figure 2). A guarantee facility can render these savings possible by pooling individual project risk and country-level risk, creating a more efficient market for projects involving electricity generation from renewable sources.

So far, multilateral cooperation on climate finance has proven to be perennially difficult, yet there is precedent for collaboration between the main multilateral development banks. Given existing international flows of public funds into renewable energy, the average yearly funding requirements of US$$_{2018}$ 29 billion until 2055 are not outright unrealistic. In future extensions of this line of work, it would be insightful to internalize the cost of participation and funding in a game-theoretical bargaining approach. This could yield valuable insights for donor countries regarding the concrete funding requirements. While the savings would most likely shift based on bargaining outcomes, the acceptance of a comparable mechanism is likely to rise. With the mechanism stepping in for considerable risks, the perception of its fairness is essential for its successful introduction and sustained operation.

Policymakers should further introduce a modest participation fee for project developers for multiple reasons. Such a fee can, first, help cover the operation and maintenance expenses of the guarantee mechanism and also offset a significant share of the mechanism's capitalization requirement. Second, it and the partial or full indemnification of the guarantee mechanism by host countries might help to reduce the moral hazard of participants in the mechanism. A future extension of our study could evaluate such moral hazard consideration on the project- and country-level and also practical and equity implications of alternative recovery options in the event of default.

Importantly, the transition to a decarbonized electricity system at the pace and scale assumed in this article will depend on the concurrent adoption of numerous other policies and measures, for instance, to create an enabling regulatory context (e.g., streamlined permitting and siting rules) and secure adequate investment in transmission, distribution, and storage infrastructure. The multilateral guarantee mechanism described in this article would, thus, be no panacea and instead need to be part of a broad portfolio of efforts at the international, national, and local level to advance the energy transition.

Still, policymakers should be aware that the estimated savings from a guarantee facility can greatly outweigh its costs, offering a powerful way of leveraging limited public funds to scale up private renewable energy investment and close the substantial gap in climate finance. Cost savings can, for instance, free up resources for adequate investments in transmission and distribution infrastructure, which form an essential condition for the uptake of a growing share of renewable resources.

Acting against climate change is ultimately inevitable. Still, the many and uncertain promises of technological advancement complicate the development of a clear path forward for all countries. Almost all possible roadmaps are linked to investment and thereby to the financial markets. Our policy proposal offers a relatively simple, but effective, and scalable instrument to promote decarbonization efforts at the global level.

Methods

We calculate the effects of a guarantee mechanism on remuneration in three steps. First, we define worldwide capacity expansion pathways for solar and photovoltaics. Second, we model multi-unit procurement auctions for renewable electricity support for 14 representative countries. Third, we calculate the CoD and CoE with and without a guarantee mechanism and feed the resulting WACC into the simulation. Note that developers use the WACC to account for risk after construction, i.e., after resolving the uncertainty modeled by the real option in our auction model. The approach, data sources and assumptions for each step are specified below.

Capacity Expansion Pathway

In the first step, we use data from Jacobson et al.[13] Their capacity expansion pathways for 100% renewable electricity supply by 2050 cover 139 countries. We take the capacity additions until 2020, 2025, and 2030 for wind onshore and solar photovoltaics, including rooftop photovoltaics and allocate equal shares of capacities to each year between 2020 and 2030.

Multi-unit Procurement Auction

In the second step, we compute demanded feed-in tariffs for the capacities using the model for multi-unit renewable electricity support auctions developed in Matthäus et al.[54] We present a brief version of the auction model here and refer the reader to their work for details on mathematical proofs and extended discussions.

We consider N risk-neutral bidders who are ex-ante uncertain about the number of competing bidders. In an auction, the government procures $K \in \mathbb{N}$ megawatt of renewable generation capacity. Each bidder $i \in \{1, \dots, N\}$ can offer and develop several projects $h \in \{1, \dots, H^i\}$. The capacity of a project is a multiple of a minimum increment of k kilowatt. Bidders submit a bid for each project, consisting of the capacity and the required feed-in tariff per MWh of electricity from that project.

We model the cost of a project using the LCOE. This measure incorporates the entire cost of electricity production, taking into account development, production, interest payments, and insurance, as well as the lifetime of the project, cf. Equation 9. If a project receives its LCOE for each MWh produced, it breaks exactly even.[56]

Due to uncertainty about future labor and material costs, among other factors, the future evolution of LCOE is uncertain at the time of bidding. Accordingly, we model the LCOE of project h of firm i as stochastic process $(L_t^{ih})_{t \geq 0}$. To ensure analytic tractability, we follow the literature on real options (e.g., Merton,[57] McDonald and Siegel,[58] Dixit and Pindyck[59]) and use a geometric Brownian motion

$$dL_t^{ih} = \mu^{ih} L_t^{ih} dt + \sigma^i L_t^{ih} dB_t^{ih}, \qquad \text{(Equation 1)}$$

where μ^{ih} is the drift, σ^i is the volatility, and $(dB_t^{ih})_{t \geq 0}$ are the increments of a standard Brownian motion with an arbitrary correlation structure. Prior to bidding at $t = 0$, each bidder privately observes two signals: the current LCOE L_0^{ih} for each of its projects h, and its volatility σ^i. We assume that L_0^{ih} and σ^i are i.i.d. continuous random variables in line with classic auction theory e.g., Riley and Samuelson[60], Myerson[61]. In the following, we omit indices i and h from processes and parameters where no confusion can arise to improve readability.

We assume a competitive environment of projects in which there is an $\varepsilon > 0$ such that the joint density $f_{L_0,\sigma}(x)$ is bounded below by ε, i.e., $f_{L_0,\sigma}(x) \geq \varepsilon$ for all x in the support.

This ensures that each bidder has competitors with similar LCOE and volatility if participation is large enough.

Bidders submit their bids b^{ih} for each project based on their signals about their own projects and their expectations about their competitors' projects. The auctioneer evaluates all bids and chooses winning projects, i.e., the lowest bids. We assume that bidders are remunerated according to uniform pricing: all projects receive the marginal bid p for one unit of electricity generated. The permission to build renewable electricity capacity for the specified feed-in tariff stays valid until time $t = T$. Bidders who do not develop their capacity within this grace period lose the permits they win in the auction.

To stimulate high realization rates, auctioneers typically charge penalties for non-realization of projects (e.g., del Río and Linares[62] and Kreiss et al.[63]). The penalty is usually implemented as a non-interest-bearing deposit posted to the auctioneer prior to the auction and refunded in the case of timely completion. To make penalties comparable to the LCOE, we scale the deposit to a payment P per unit of energy.

We populate our model with two types of bidders: naive bidders who determine their valuation according to net present cost (NPC) and bidders who determine their valuation according to (real) option based cost (OBC). NPC bidders fail to recognize the flexibility of non-realization embedded in the auctioned contracts, while OBC bidders factor it in. Existing literature provides evidence for the existence of both bidder types,[64–74] Paddock[64], Quigg et al.,[65] Graham and Harvey[66] Moel and Tufano[67] Cunningham[68] Bulan et al.,[69] Denison et al.,[70] Wang et al.,[71] Kellogg,[72] Holst et al.,[73] Ihli et al.,[74] and Matthäus et al.[54] investigate the matter empirically for the case of renewable electricity support auctions in the United Kingdom and Germany. The empirical approach elicits a share of 35% NPC bidders in the German auction for offshore wind support, which we employ in the present model as well.

We use a risk-neutral approach to determine project valuations for both bidders. Following standard theory Black and Scholes[75] and Duffie[76], we define a constant risk-free interest rate r and a risk-free version of the LCOE process

$$dL_t^* = rL_t^* dt + \sigma L_t^* dB_t^*, \qquad \text{(Equation 2)}$$

where $(dB_t^*)_{t \le 0}$ are the increments of the Brownian motion under the equivalent martingale measure $\mathbb{Q}$. The discounted process $e^{-rt}L_t^*$ is a martingale under $\mathbb{Q}$. Hence, $\mathbb{E}_0^*(e^{-rt}L_t) = L_0$, with $\mathbb{E}_0^*$ the expectation at time $t = 0$ under $\mathbb{Q}$. Consequently, NPC bidders are indifferent when to develop a project. To simplify the comparison with OBC bidders, we assume that for NPC bidders the awarded contract is equivalent to a standard forward contract with maturity at T and risk-free price $\mathbb{E}_0^*[L_T] = e^{rT}L_0$. Accordingly, the expected net present value per MWh for an NPC bidder equals the discounted difference between the tariff p the bidder receives and the expected LCOE at time T, i.e.,

$$NPV(L_0, p) = e^{-rT}(p - e^{rT}L_0). \qquad \text{(Equation 3)}$$

OBC bidders are interested in the value W^{ih} of the European put option with maturity $t = T$ and payout profile per unit capacity.

$$max(p - L_T, -P). \qquad \text{(Equation 4)}$$

In contrast to standard put options, the payout can be negative and is bounded below by $-P$, reflecting the penalty for non-realization. Using standard arguments for risk-neutral valuation, the option value is given by

$$W^{ih}\left(L_0^{ih}, \sigma^i, p, P\right) = -L_0^{ih}\Phi(z) + e^{-rT}\left((p+P)\Phi\left(z+\sigma^i\sqrt{T}\right) - P\right), \quad \text{(Equation 5)}$$

$$z := -\frac{\ln\frac{L_0^{ih}}{p+P} + \left(r + \frac{\sigma^{i2}}{2}\right)T}{\sigma^i\sqrt{T}},$$

where Φ is the cumulative distribution function of a standard normal distribution.

Bidders determine their bids based on their valuation. Following arguments from asymptotic auction theory,[77,78] we can assume that bidders bid truthfully, i.e., bid their reservation price. For NPC bidders, this is

$$0 = \mathbb{E}_0^*\left[NPV\left(L_0^{ih}, p\right)\right] = e^{-rT}\left(p - \mathbb{E}_0^*\left[L_T^{ih}\right]\right) = e^{-rT}\left(p - e^{rT}L_0^{ih}\right), \quad \text{(Equation 6)}$$

which yields a reservation price of

$$NPC\left(L_0^{ih}\right) := e^{rT}L_0^{ih}. \quad \text{(Equation 7)}$$

For OBC bidders, the unique $OBC(L_0^{ih}, \sigma^i, P)$ is implicitly defined by

$$W^{ih}\left(L_0^{ih}, \sigma^i, OBC\left(L_0^{ih}, \sigma^i, P\right), P\right) = 0. \quad \text{(Equation 8)}$$

We simulate bids for renewable electricity support auctions in 14 countries representing 14 regions (cf. Table 1) for 11 years between 2020 and 2030. To employ the model, we require data on the regulatory framework (K, T, P), data on the surrounding economic environment (r), and data concerning bidders (N, σ, L_t).

We use auctioned capacity K from Jacobson et al.[12] as previously described, assume a maturity of 4.5 years and a penalty of 15,000 US$_{2018}$/MW for offshore wind and 50,000 US$_{2018}$/MW for solar photovoltaics, based on the German legislation.[79] The penalty translates to cost P of 0,2–1,3 US$_{2018}$/MWh and 1,6–4,8 US$_{2018}$/MWh, respectively, depending on capacity factors and risk-free rates of the regions in our model, assuming the lifetime of a plant equals 25 years. For risk-free rates, we use the average yield of 10-year government bonds in 2018 for the respective representative country of each region.

To elicit N, we take the average participation of past auctions in Germany and find that about 150 bidders participate per 1,000 MW auctioned, each bidder offering between 1 and 3 projects with equal probability. Volatilities range between 0% and 15% according to Kost et al.[80] for which we assume a symmetric triangular distribution. To incorporate variability in the quality of the construction site, we use the approach of Heck et al.[81] who sample LCOE for different technologies by treating the inputs of the LCOE calculation as random variables.

The basic LCOE formula of Heck et al.[81] given in Equation 9 comprises an annual payment A, associated with initial capital expenditure, fixed operation and maintenance cost $O\&M_F O\&M_F$, a capacity factor C_f of the plant, and variable operation and maintenance cost $O\&M_V O\&M_V$:

$$LCOE = \frac{A + O\&M_F}{8760 \cdot C_f} + O\&M_V. \quad \text{(Equation 9)}$$

The formula for the annualized payment A is given in Equation 10 and depends on the WACC w, the capital expenditure of the cost C_c, and the number of payments n, assumed to be the lifetime in years of the plant:

$$A = C_c\left[w + \frac{w}{(w+1)^n - 1}\right]. \quad \text{(Equation 10)}$$

Further, Heck et al.[81] propose probability distribution and ranges of support for different technologies in the United States. We adapt their setting for our representative countries.

For $O\&M_F$, $O\&M_V$, and C_c we determine the base cost case relying on Kost et al.[80] and Heck et al.[81] and use a capital scalar proposed by Morris et al.[82] to scale it to a regional level. The capital scalar accounts for region-specific cost of labor and capital, among others. We source capacity factors from Jacobson et al.[12] and scale the values to the support for probability distributions based on Matthäus et al.[54] and Heck et al.[81] We discuss our approach to calculate the WACC w below. We include a list of parameters used in the simulation in the online appendix, cf. Tables S1 and S2.

Risk Reduction and Effect on Cost of Debt and Cost of Equity

In the third step, we vary the WACC w for a case with and without guarantee mechanism to reflect a change in investment risk after resolving the uncertainty modeled by the real option. Varying w affects LCOE via Equation 10 and thereby changes bids via Equations 7 and 8.

The WACC is defined as

$$WACC = CoD\frac{D}{D+E} + CoE\frac{E}{D+E}, \quad \text{(Equation 11)}$$

with CoD the cost of debt, CoE the cost of equity, and E and D the amount of equity and debt, respectively. For our simulation, we use a debt share of 80% for all technologies and countries according to industry standard 18. To construct country-level CoD and CoE, we start from the risk-free rates r based on the yield of 10-year government bonds and add a default risk spread (DS) or an equity risk premium (ERP), respectively.[55] This yields

$$CoD = r + DS, \text{ and} \quad \text{(Equation 12)}$$

$$CoE = r + ERP. \quad \text{(Equation 13)}$$

Estimated CoD and CoE are very close to industry data, where the latter is available. We opt for a consistent database in our model and use numbers based on Damodaran[55] throughout and do not differentiate WACC for different technologies. We assume that a guarantee mechanism reduces the WACC by the default risk spread, reducing the risk of failure to pay. We include the parameters on financing cost used in the simulation in the online appendix, cf. Tables S1 and S2.

EXPERIMENTAL PROCEDURES

Resource Availability

Lead Contact

David Matthäus

Materials Availability

This study did not generate new unique materials.

Data and Code Availability

The datasets and code generated during this study are available at Mendeley Data: https://dx.doi.org/10.17632/rdhys9n968.1.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.joule.2020.10.011.

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AUTHOR CONTRIBUTIONS

Conceptualization, D.M.; Methodology, D.M. and M.M.; Software, D.M.; Validation, D.M. and M.M.; Formal Analysis, D.M.; Investigation, D.M.; Data Curation, D.M.; Writing – Original Draft, D.M. and M.M.; Writing – Review & Editing, D.M. and M.M.; Visualization, D.M.; Supervision, D.M. and M.M.; Project Administration, D.M.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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