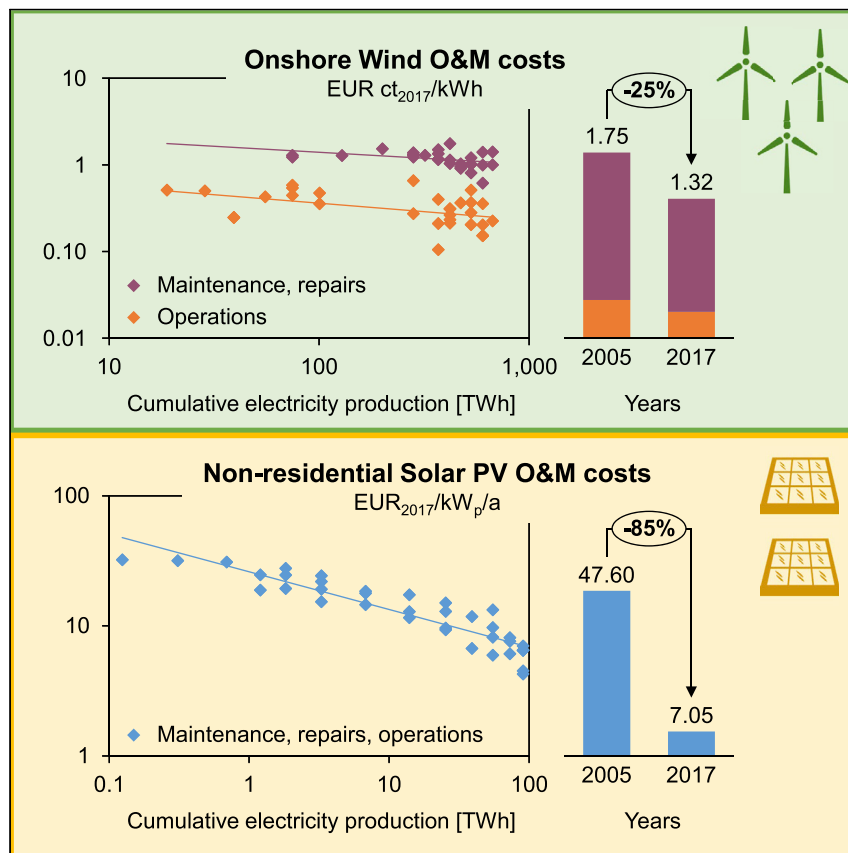


Article

Experience Curves for Operations and Maintenance Costs of Renewable Energy Technologies



Operations and maintenance (O&M) cost for renewables become increasingly important, accounting for 20%–25% of lifecycle costs for wind and solar plants in 2017. Understanding the dynamics of these costs will allow to increase the precision of modeling results in energy system and integrated assessment models and improve planning by various stakeholders. We estimate O&M experience curves for renewable energy technologies, evaluate mechanisms regarding how O&M experience led to lower costs, and demonstrate a projection of O&M costs until 2030.

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HIGHLIGHTS

New data show O&M cost for onshore wind and solar PV strongly improved over time

Underlying learning mechanisms support applying the experience-curve concept

Experience rates between 9.2% and 18.2% estimated for different cost components

Endogenizing O&M cost dynamics can improve precision of energy system models

Article

Experience Curves for Operations and Maintenance Costs of Renewable Energy Technologies

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SUMMARY

Given the decline in investment costs for renewable energy technologies, other cost components have become increasingly important. In 2017, operations and maintenance (O&M) accounted for 20%–25% of lifecycle costs for wind and solar plants in Europe, but the understanding of O&M dynamics is limited. Presenting new data from Germany, here, we consider cumulative operating experience to estimate O&M experience curves for onshore wind and solar photovoltaic (PV). Results indicate O&M cost reductions with each doubling of cumulative experience of 9.2%–12.8% for onshore wind and of 15.7%–18.2% for solar. Drawing on expert interviews and archival information, we describe mechanisms regarding how O&M experience led to lower costs, including economies of scale, upsizing, learning by doing, and learning by using and learning by interacting, comparing both technologies. Moreover, regulatory changes fostered competitive pressure toward cost reductions. Our results suggest that dynamic cost reduction potentials for O&M need to be considered in energy system planning, modeling, and optimization.

INTRODUCTION

Renewable energy (RE) technologies are considered a key lever for climate change mitigation.^{1,2} Accordingly, policy-driven RE deployment over the last two decades led to rapidly increasing installed capacities of onshore wind and solar photovoltaic (PV) while improving the technical maturity and cost position of these technologies.^{3–7} For instance, the levelized cost of electricity (LCOE) from wind power in Germany decreased from 113 to 62 USD per MWh during 2000–2017 and for PV from 500 to 67 USD in the same period.⁸ A clear understanding of these cost dynamics, including projections for future costs, is required to allow for sound investment decisions.^{5,9} RE cost dynamics are also a decisive factor for efficient technology portfolios as derived by energy system or integrated assessment models¹⁰ and as such feed into energy and climate policy making.

For RE investment costs, it is a well-established approach to describe the cost dynamics through experience curves, postulating that costs decrease by a fixed percentage for each doubling of the cumulative installed capacity.^{11,12} For wind turbines and PV modules, many studies estimate experience rates^{12,13} and provide innovation theory-based justifications for the functional link between cumulative deployment and cost.^{14–16} Since the share of investment costs for wind turbines and PV modules in the LCOE strongly decreased over the last decade, researchers recently started to assess the dynamics of non-investment cost components (or “soft costs”),¹⁷ such as installation cost^{18,19} and financing cost.⁸ However, extant

Context & Scale

Energy scenarios in line with the Paris Agreement suggest massive investments in wind turbines and solar photovoltaics (PVs). Thus, understanding their cost reduction dynamics is key to detail feasible transition pathways and to identify necessary support measures. Past research mainly studied the development of equipment and installation cost. However, other cost components gain in importance. Here, we study operations and maintenance (O&M) costs and deliver a quantitative and qualitative description of their dynamics. Our results are based on data for wind turbines and solar PV systems in Germany but have global implications. The depiction of O&M cost dynamics by experience curves allows to project future cost reductions, informing energy system planning and the design of support policies. For researchers, the method allows to endogenize O&M cost dynamics in energy system and integrated assessment models, improving the precision of scenarios and the informational value of modeling results.

research has hardly scrutinized expenses for operations and maintenance (O&M).²⁰ These expenses are non-negligible—in 2017, O&M costs are estimated at 20%–25% of RE LCOE in Europe.^{21,22} One reason for this research gap is the lack of data as O&M costs for utility-scale plants are determined in customized, non-disclosed service contracts and have rarely been systematically collected in a comparable way.^{20–22} As a consequence, energy system modelers rely on rough approximations for O&M cost (values per kW often assumed to be fixed over decades²³ or percentage mark-ups on the investment costs²⁴). With the increasing relative importance of soft costs for the LCOE of RE, such simplifications are problematic.²²

To address this gap, here, we analyze the development of O&M cost for onshore wind and utility-scale PV in Germany—a country with a particularly long deployment history in both technologies.²⁵ We collect new data for historical O&M contracts signed during the period from 2000 to 2017, and for the first time, allowing a comparison of O&M cost dynamics between the two most relevant non-hydro RE technologies. First, we categorize activities into a standardized O&M scope to allow for a meaningful comparison across projects. Second, we estimate O&M experience curves for both technologies, revealing a substantial decrease in O&M costs with increasing operating experience. Drawing on 31 expert interviews and 543 archival documents, we next analyze the underlying drivers and add to the literature by assessing whether the empirical relationship between O&M cost and experience can be related to principles of innovation theory. We then discuss how the different dynamics of wind and PV O&M can be related to technology-inherent characteristics. A discussion of implications, including projections of further cost dynamics until 2030, concludes the article.

RESULTS

Scope of O&M for RE Technologies

While wind turbines and PV plants do not require expenditures for fuel as do conventional power plants, they are similar to other technologies in that operating expenses occur over the lifetime of assets. Such costs relate to a variety of tasks commonly referred to as O&M (other costs not discussed here include fixed land lease and insurance fees). For utility-scale plants, O&M services are typically procured from specialized service providers. As the scope of procured services varies, comparing the costs between plants is a challenge.²⁰ To address this, we analyzed O&M contracts and service descriptions (see [Experimental Procedures](#)) to define a clear scope of O&M, as summarized in [Figure 1](#).

For onshore wind, maintenance and repairs make up the lion's share, with ca. 85% of O&M costs. In Europe, these services are typically procured in full service contracts from wind turbine original equipment manufacturers (OEMs) or specialized companies with capabilities for servicing the rotating equipment and for working at great heights. For solar PV, maintenance and repairs are procured from less-specialized licensed electricians and make up only a small share of O&M costs (cf. [Table 1](#)). However, ground-mounted PV systems require dedicated site management, in the German climate mainly green keeping, which makes up about a third of O&M costs for PV. For both technologies, various white collar tasks for operations, technical and commercial management (in the following termed “operations” for simplicity) need to be conducted off-site—either in-house by a department at the asset owner (which is often the case for plants owned by utilities) or externally by specialized asset management companies (which is often the case for plants owned by investment funds in project finance structures²⁶). We consistently use the definition of the O&M scope in [Figure 1](#) for the quantitative analyses we present below.

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Scope of O&M for onshore wind	Typical share of O&M cost
Wind turbine maintenance and repairs ▪ Bi-annual inspection and preventive maintenance, testing of safety-related equipment ▪ Corrective maintenance, esp. replacement of wear and tear parts, repair of components defects, replacement of gearbox ▪ Other (e.g. spare part management, tower motion survey)	85%
Operations and technical management ▪ Continuous performance monitoring and reporting ▪ Plant control, interface with grid operator/off-taker ▪ Other (e.g. warranty and insurance claim management)	15%
Commercial management ▪ Financial management, accounting and tax reporting ▪ Other (e.g. interface with local authorities)	
Wind turbine site management ▪ Other (e.g. maintenance of access roads, maintenance of environmental compensation measures)	0% (only in special cases)
Scope of O&M for utility-scale PV	Typical share of O&M cost
Solar PV plant maintenance and repairs ▪ Annual inspection and preventive maintenance ▪ Corrective maintenance, esp. cabling repairs, exchange of defect PV modules and inverters ▪ Other (e.g. spare part management)	40%
Operations and technical management <i>Same tasks as for onshore wind</i>	28%
Commercial management <i>Same tasks as for onshore wind</i>	
Solar PV site management ▪ Vegetation management/green-keeping ▪ Other (e.g. module cleaning, snow clearing, security)	32%

Figure 1. Scope of O&M Costs for Onshore Wind and Utility-Scale PV

Based on an analysis of contracts and service descriptions for Germany (see [Experimental Procedures](#)). Percentages for the share of cost components are values for 2017, estimated from the data collected in this study.

Analyzing the Dynamics of RE O&M Cost

To establish whether experience curves appropriately describe the development of O&M cost for RE technologies, we use a mixed methods approach, combining (1) a quantitative analysis of the empirical relationship between cumulative operating experience and O&M cost and (2) a qualitative analysis on whether past cost reductions can be related to principles of innovation theory.

Table 1. Estimates of Experience Curve Model Coefficients for Onshore Wind

	Maintenance and Repairs			Operations		
	Model I	Model II	Model III	Model I	Model II	Model III
Constant (α)	0.4230*** (0.1507)	0.4230** (0.1689)	0.4506*** (0.1402)	−0.0515 (0.1387)	−0.0515 (0.1250)	−0.0405 (0.1650)
Cumulative production (β)	−0.1396** (0.0617)	−0.1396* (0.0693)	−0.1410** (0.0576)	−0.1957*** (0.0594)	−0.1957*** (0.0549)	−0.1976*** (0.0647)
Community wind farm (δ_1)	NA	NA	−0.0467 (0.0369)	NA	NA	−0.0089 (0.0569)
Gearless turbines (δ_2)	NA	NA	0.0246 (0.0210)	NA	NA	NA
SE distribution	robust	clustered	robust	robust	clustered	robust
R ²	0.141	0.141	0.203	0.232	0.232	0.232
N	30	30	30	30	30	30

Models I and III use Huber-White-Sandwich estimators for standard errors, and Model II specifies that standard errors are clustered at the level of data providers (developers or owners or service companies, 18 clusters). The additional control variables in Model III cover structural aspects that are independent from O&M experience.

*Statistically significant at 10%.

**Statistically significant at 5%.

***Statistically significant at 1%.

Standard errors (SE) in parentheses.

In the quantitative analysis, we build on the assumption that accumulating experience in the delivery of O&M services leads to cost reductions.¹¹ The empirical observation that costs often decrease by an approximately fixed percentage with each doubling of cumulative production led to the widely used experience curve model^{11,12,27}

$$C_t = C_0 \left(\frac{x_t}{x_0} \right)^b, \quad (\text{Equation 1})$$

where in our case C_t is the O&M cost in year t , x_t is the cumulative production in year t , C_0 is the O&M cost in year 0, and b is the rate of cost reduction.

In the case of O&M services, the relevant experience is accumulated by operating and servicing assets, so here, x_t describes cumulative energy produced in MWh. The experience curve model, thus, differs from the typical specification for investment costs, where cumulative installed capacity (MW) is used as explanatory variable.^{12,13} (While cumulative installed capacity [MW] and cumulative energy produced [MWh] are often highly correlated during early deployment, they can differ markedly in later years.) The reason for using cumulative energy production (MWh) and not cumulative capacity additions (MW) for the O&M experience curve is underlined by the following thought experiment: If a fleet of wind turbines is being installed but then never used, one would still expect experience effects contributing to lowering investment costs (because the turbines are manufactured and installed) but not experience effects for O&M (because the turbines are never operated or maintained). If in contrast, the capacity deployment of wind turbines comes to a halt, but the existing fleet continues to operate, one would expect experience effects in O&M (because the turbines are operated and maintained) but no further improvements of investment costs. These theoretical considerations are supported by empirical evidence from qualitative interviews (see below) that support the choice of cumulative energy produced as measure for O&M experience. An empirical case in point is solar PV: While utility-scale deployment in Germany almost came to a halt after 2012 (compare Figure S3), electricity production in existing plants of course continued, operators gained additional experience and

Box 1. Experience Mechanisms from Innovation Theory

The innovation literature has identified several mechanisms that explain the empirical observation of decreasing cost with increasing cumulative deployment and the use of a product or service.^{28–31} Most of these mechanisms are related to learning within and across organizations, as follows:

- Economies of scale: reduced cost due to increased scale of operations (e.g., fixed costs distributed over more units)
- Learning by doing: a firm or industry learns by repeated practice in producing a product or delivering a service (e.g., optimizing a service based on experienced problems)
- Learning by using: a firm or industry learns by using a product or service (e.g., improved operation practices with a product based on experience with that product)
- Learning by interacting: a firm or industry learns through the interaction with other actors up- or downstream of the supply chain (e.g., improving the design of a service based on feedback from users of the current design)

In addition to experience mechanisms, cost reductions can also be driven by factors that are typically not directly linked to cumulative experience, such as upsizing of product units, spillovers from advances in other technologies and changes to regulation and market structure.

optimized their O&M service contracts, and the overall O&M service industry kept improving.

From Equation 1, the percentage O&M cost reduction associated with a doubling of the cumulative energy produced (i.e., the experience rate) is given by

$$ER = 1 - 2^b. \quad (\text{Equation 2})$$

For an empirical estimation, Equation 1 can be rewritten in the common logarithmic form as

$$\log(C_t) = \alpha + \beta \log(x_t) + \delta D_t + \epsilon_t, \quad (\text{Equation 3})$$

where $\alpha = \log(C_0)$, $\beta = b$, D_t is a vector of control variables, and ϵ_t is the error term. For details on the empirical approach see [Experimental Procedures](#).

In the qualitative analysis, we draw on archival documents and 31 expert interviews to distil the drivers of past improvements—these are then categorized according to whether they are related to experience in RE production (experience mechanisms based on innovation theory, see [Box 1](#)) or whether they are unrelated to experience (e.g., changes to regulatory structure). See [Experimental Procedures](#) for more details on the qualitative approach.

Experience Curve and Drivers for Onshore Wind

Following the structure of typical service contracts in Europe, the O&M costs for wind turbines depend on the energy produced and are expressed in EUR ct per kWh. Operations costs are typically reported separately from maintenance costs; hence, we analyzed these separately. As the latter vary over the lifetime of an asset, here, we focus on the representative five-year period (asset age 4–8) that starts after initial OEM guarantees run out and finishes before O&M cost rises in the second decade of asset life (see [Experimental Procedures](#) and [Figure S1](#)).

[Figure 2A](#) exhibits O&M cost and experience curves for onshore wind, showing that maintenance and repair costs per MWh are about five times higher than operations costs. In sum, onshore wind O&M cost decreased from an average 1.75 EUR ct₂₀₁₇/kWh in 2005 to 1.32 EUR ct₂₀₁₇/kWh in 2017, a reduction of 25% ([Figure 2B](#)). [Table 1](#) provides

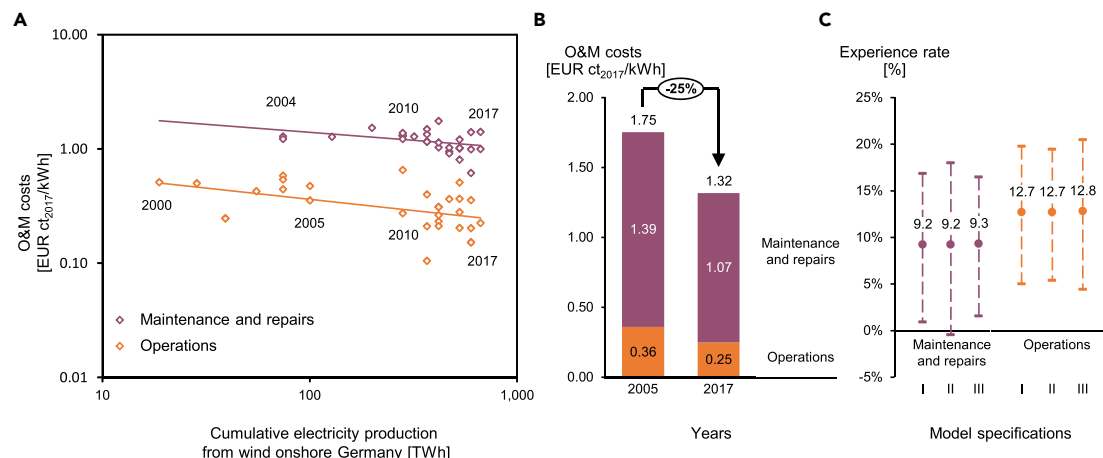


Figure 2. Onshore Wind O&M Experience Curves

(A–C) Images show O&M cost data and experience curve estimates in Model I specification (A), cost reductions over time (B), and interval estimates (95%) for experience rates in different model specifications (C).

estimated experience curve parameters in different model specifications, and Figure 1C illustrates the corresponding experience rates. Point estimates for the maintenance and repairs experience rate are at 9.2%–9.3%, and for operations at 12.7%–12.8%. Confidence intervals are relatively large due to the scatter in the data, but the experience rates are statistically significantly larger than zero at the 95% level for all specifications except for one (see Figure 2C).

A synthesis of cost reduction drivers from the qualitative analysis highlights that several important drivers are related to experience mechanisms (cf. Box 1) and hence supports the experience curve relationship from an innovation-theory point of view: First, wind turbine operators and O&M service providers could realize “economies of scale” with larger portfolios of turbines to be serviced and with less distance between farms. For instance, the density of wind capacity in Schleswig-Holstein (Germany’s state with the highest share of wind power) increased from 0.03 to 0.42 MW/km² during 1996–2016.^{32,33} Economies of scale at the service provider level could also be realized thanks to a consolidation of the wind turbine OEM industry because a reduced variety of turbine types to be served simplified the spare part management for some companies (see Figure 3). The overall growth of the sector also allowed improved efficiency of the wind O&M industry as a whole, such as through specialized vocational training programs.

Second, “learning by doing” yielded improvements in processes and routines both in maintenance and in operations, such as through the growing experience of technicians and better use of preventive maintenance interventions. On the level of plant owners, shifting to shorter service contracts allowed to increase the cost pressure for O&M suppliers.

Third, on the industry level, “learning by using” and “learning by interacting” resulted in better serviceability of new turbine generations, particularly through increased use of SCADA data (supervisory control and data acquisition, a control system for wind turbines). Such improvements built on feedbacks from the use phase to turbine design within companies, which act both as OEM and service provider but also through inter-company interaction in regular industry meetings. Particularly in the earlier years of the O&M industry, technical incident reporting to the public scientific measurement and

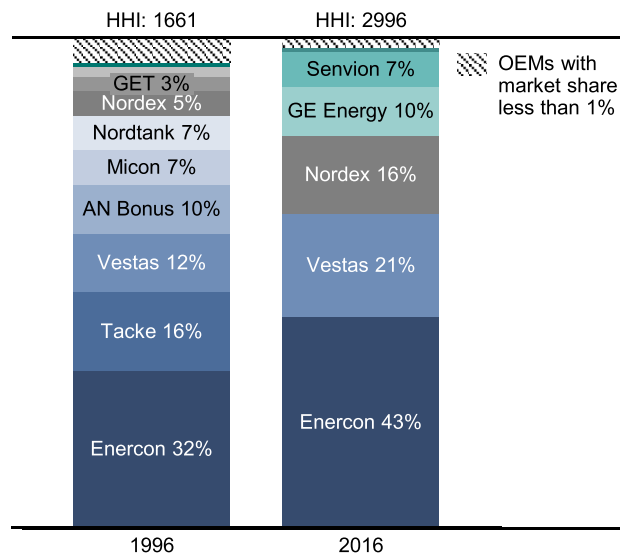


Figure 3. Consolidation of Onshore Wind Turbine Industry

Columns show the market share of OEMs for turbines installed in 1996 and 2016 in Germany.^{32,33} The Herfindahl Hirschman index (HHI) measures market concentration, with 1 being atomistic competition and 10,000 being a monopoly.

evaluation program (WMEP)³⁴ (mandatory for many recipients of wind energy subsidies) created a high level of transparency concerning malfunctions and causes of failure for individual turbine types, which helped to improve turbine design and O&M practices alike.

Besides these channels that link cost reductions to increased experience in deployment and operation, we also identified several factors unrelated to experience. The “upsizing” of individual wind turbines led to major unit cost reductions in O&M. With increased deployment, the average turbine size increased 5-fold between 1996 and 2016 (from 550 kW to 2.8 MW),^{32,34} reducing maintenance work on a per kW basis (as tasks that needed to be done in five turbines separately can now be done in a single turbine instead). Possibly accelerating cost reductions, some “spillovers from advances in other technologies” helped the wind O&M industry, such as mobile internet for service teams and drones for blade inspections. However, the expert interviewees assessed the impact of these technologies on wind O&M cost until 2017 as rather small. An often-mentioned factor potentially slowing down cost reductions is the “market structure” for maintenance and repair services. The rapid wind power deployment over many years led to a “seller’s market” for OEMs in Germany, and signing a 20-year service contract was sometimes a prerequisite for being able to secure turbines in the first place. In these cases, the O&M costs to be paid by the turbine owner were locked-in for the entire lifetime of a turbine, and the pressure for cost reductions at the service provider was limited. Only recently did the market structure start to shift, with more independent service providers offering maintenance for turbines from multiple OEMs, which is expected to increase competitiveness and hence, the pressure for cost reduction of their services.

Experience Curve and Drivers for Solar PV

Unlike for wind, the O&M costs for solar PV plants in Europe are typically reported as total cost for O&M and expressed in EUR per kW_p. Figure 4 exhibits our O&M cost and experience curves. In sum, solar PV O&M cost decreased from an average of 47.60 EUR₂₀₁₇/kW_p/a in 2005 down to 7.05 EUR₂₀₁₇/kW_p/a in 2017, a remarkable reduction of 85% (Figure 4B). Point estimates for experience rates (Figure 4C) are

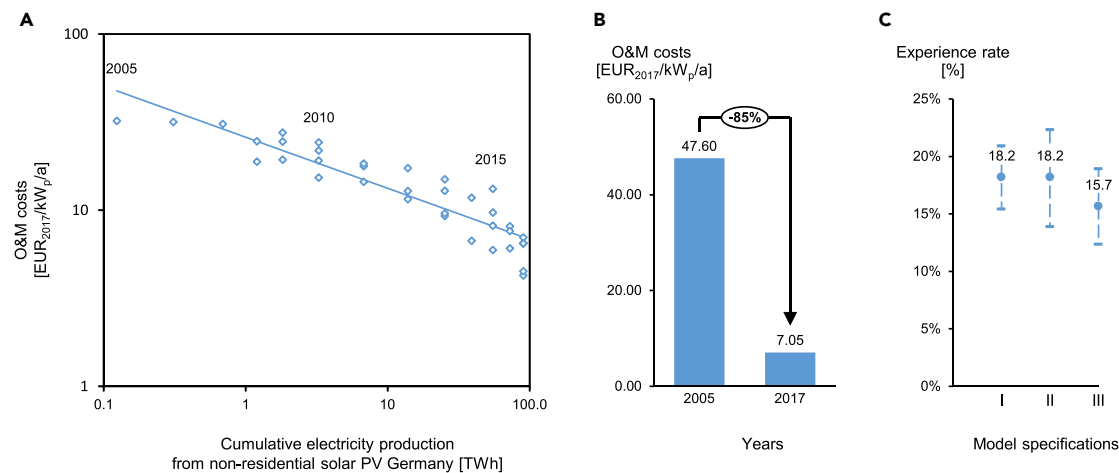


Figure 4. Solar PV O&M Experience Curves

(A–C) Images show O&M cost data and experience curve estimates in Model I specification (A), cost reductions over time (B), and interval estimates (95%) for experience rates in different model specifications (C).

between 15.7% and 18.2%, and the confidence intervals are much smaller than for onshore wind. Table 2 provides estimated parameters for different model specifications. As the regulatory environment for solar PV changed with the introduction of auctions, Model III includes a dummy variable for the auction years 2016–2017 (in Germany, auctions for solar PV were introduced earlier than for onshore wind); O&M costs are significantly lower in these years.

Also, in the case of PV, the qualitative analysis distilled several drivers for cost reduction that are related to experience mechanisms (cf. Box 1). First, also PV service providers were able to realize “economies of scale.” The plant portfolios of individual service providers became larger and plant sites geographically denser as installed capacity increased at a compounded annual growth rate of 42% from 2005 up to 2017 (compare Figure S2). These factors led to a fixed cost digression of O&M providers’ overhead and for systems such as remote monitoring software as well as reduced travel times and allowed for simplifying spare part management.

In addition, strong improvements stem from “learning by doing”: the scope of O&M services was reduced as firms understood which services were essential and at what frequency they were needed in order to ensure a plant’s performance. One example is the inspection of the grid connection equipment, which does not need to be done every year with the same scope if aligned with the grid operator. In some cases, the frequency of module cleaning could also be reduced. O&M contracts were increasingly modularized and standardized and contract durations were reduced. Especially after the introduction of the auction-based remuneration for PV electricity in Germany, O&M providers renegotiated contracts for individual services and utilized O&M service tenders to achieve cost reductions. In addition, many smaller process improvements were achieved over time, supported by the increasing digital capabilities of firms.

Furthermore, improvements were realized through “learning by using” and “learning by interacting”: the needs of O&M services providers were increasingly considered even in the design phase for new PV plants. Important improvements are module row layouts that enable faster green-keeping and plant designs using

Table 2. Estimates of Experience Curve Model Coefficients for Solar PV

Total O&M			
	Model I	Model II	Model III
Constant (α)	1.4150*** (0.0288)	1.4150*** (0.0213)	1.3993*** (0.0239)
Cumulative production (β)	−0.2898*** (0.0238)	−0.2898*** (0.0333)	−0.2461*** (0.0277)
Auction year (δ)			−0.1322** (0.0494)
SE distribution	robust	clustered	robust
R ²	0.838	0.838	0.871
N	37	37	37

Models I and III use Huber-White-Sandwich estimators for standard errors, and Model II specifies that standard errors are clustered at the level of data providers (developers or owners or service companies, 11 clusters).

The additional control variable in Model III covers a structural aspect that is independent from O&M experience, namely a change to the regulatory environment (introduction of competitive auctions).

*Statistically significant at 10%.

**Statistically significant at 5%.

***Statistically significant at 1%.

SE in parentheses.

smaller string inverters instead of larger central inverters, which makes them easier to service and by less specialized personnel.

One key difference between wind and solar PV is the effect of “changes to the regulatory environment,” which were mentioned in every single interview. In particular, two policy changes have affected the solar PV O&M market. First, with revisions of the RE sources law in 2012,^{35–37} the level of the feed-in tariff was strongly reduced and new deployment limited to between 2.5 and 3.5 GW_p per year (after more than 7 GW_p in the three years before). As a consequence, many project developers entered the O&M business in search of alternative revenue opportunities as well as more stable and predictable future cash flows. Second, the feed-in tariff for ground-mounted plants was replaced by an auction-based system in 2015–2016.³⁸ According to our interviewees, this led firms to challenge every cost element in detail in order to be able to compete. Thus, competitive pressure increased, reducing profit margins for the involved parties and further reducing the prices of O&M service contracts.

DISCUSSION

Comparison of O&M Dynamics between Technologies

The combined evidence from the quantitative and qualitative analyses presented here underscores that using an experience curve model to describe the dynamics of O&M costs is well justified for both onshore wind and solar PV. The underlying experience mechanisms thereby exhibit differences that are in line with technology-inherent characteristics as postulated by innovation theory.^{16,39–41} Learning by doing, on the one hand, has been particularly important for the simpler and more modular technology solar PV,^{16,39} where O&M contracts were increasingly modularized, allowing for the successive reduction of service scopes and competitive procurement of individual services. Wind turbines, in contrast, are a more complex technology with more subsystems and linkages between them^{16,39} and are consequently mostly serviced from a single provider in less competitive service markets. The potential for learning by using and learning by interacting, on the other hand, is typically larger for more complex technologies⁴¹—and consequently has been particularly important for onshore wind, where many improvements in service-ability have been made based on service feedback on earlier turbine generation.

Finally, in this study we also observe differences due to the introduction of auctions for solar PV, which however is a coincidence of regulatory changes in Germany during 2015–2016 (two years later auctions were also introduced for onshore wind).

For both technologies, the qualitative evidence suggests that economies of scale have been a particular important improvement driver during the earlier years of commercial deployment (in the 1990s for onshore wind, and in the 2000s for utility-scale PV). Learning by doing, learning by using, and learning by interacting were important drivers throughout our study period, though the channels for learning by interacting partly changed (e.g., for wind onshore, first via mandatory technical incident reporting and later via exploitation of SCADA data; see also Figure S2).

Quantitatively, the estimated experience rates for onshore wind O&M of 9.2%–9.3% (maintenance and repairs) and 12.7%–12.8% (operations) are close to typical experience rates for the capital cost of onshore wind (on average reported at 10%–12%).^{12,42} The experience rate for solar PV O&M (18.2%) is higher than for wind, even after controlling for the auction effect (15.7%)—though clearly below typical rates for the capital cost of solar PV (on average reported at 23%).¹² While this study provides the first comparison of O&M dynamics between RE technologies, relating the quantitative differences to technology-inherent characteristics will require further research on a larger set of technologies.

Implications and Conclusion

The O&M cost dynamics presented in this article have implications for various stakeholders. First, actors in the RE sector such as project developers and asset owners should embrace that onshore wind and solar PV plants hold a cost reduction potential also after commissioning. Consequently, it is worth considering the serviceability of plants already during project development, including keeping the flexibility for later improvements for instance through O&M contracts of shorter duration or with flexible clauses. More generally, a greater relative importance of O&M costs suggests to abandon the paradigm of RE being an “invest and forget” asset class, but to actively manage the continuous improvement of operating expenses.

Second, policymakers aiming at a cost-efficient low-carbon transition should likewise keep the cost reduction potential of O&M costs (which can make up 20%–25% of LCOE)^{21,22} in mind. Business experience shows that companies engage in cost optimization of (labor-intensive) service processes typically only if competitive pressure is high, as it was the case for solar PV O&M in Germany particularly after the introduction of competitive auctions. If competition is less pronounced, as arguably the case for onshore wind maintenance where OEMs possessed vertical market power, cost improvements might take longer to materialize. Therefore, our illustration of improvement potentials in O&M costs adds to the appeal of competition-increasing policy instruments such as auctions, at least for mature technologies in established markets such as wind and PV in Germany.

Third, researchers could make use of the experience curve pattern to enhance the representation of O&M costs in energy system and integrated assessment models and thus improve the precision of scenarios. While such additional model complexity might have been unnecessary a decade ago, the growing relative importance of O&M costs suggests a reassessment of the models to that end. To illustrate a potential future dynamic for the case of Germany, Figure 5 projects onshore wind and PV O&M costs until 2030 and compares these to assumptions that are commonly used in German energy

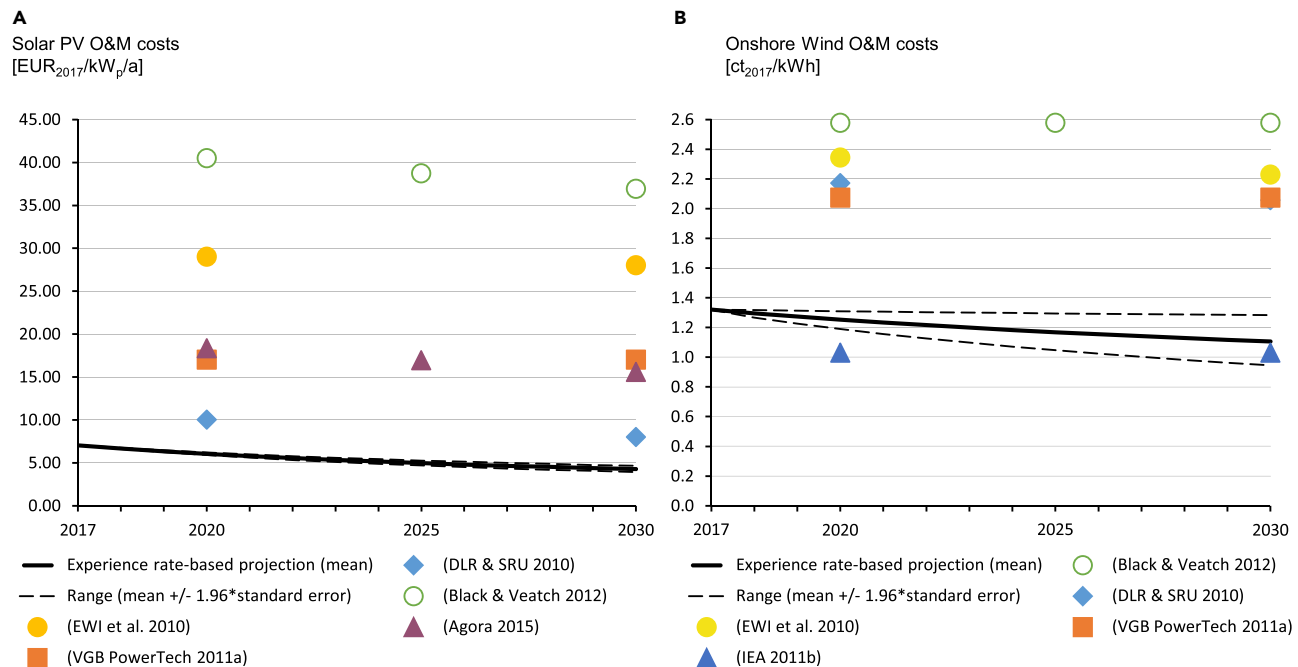


Figure 5. Comparison of Solar PV and Onshore Wind O&M Cost Projections from the Experience Rates Established in This Study with Point Estimates from Various Reports

Qualitative evidence supports the potential for further cost reductions as per our quantitative projections (see Table S2). The point estimates are taken from a review for Germany,²³ which is commonly used as input for energy system models (see Experimental Procedures).

system models (see Experimental Procedures). The projection highlights that static assumptions (dating back to cost data from 2010–2015) seem to overestimate costs compared to experience-curve-based projections. Accordingly, endogenizing O&M costs through experience curves could lead to different model outcomes. The importance of O&M cost dynamics for future LCOE will depend on the dynamics of other input parameters as well (e.g., financing costs⁸ and full load hours⁴³), a comprehensive sensitivity analysis is an area for future research.

To conclude, we hope that this article serves as a starting point for further research on the dynamics of RE O&M. Larger datasets could help to achieve narrower interval estimates particularly for onshore wind O&M experience rates in Germany. Analyses should be extended also to other regions to quantify experience rates and study the impact of structural differences across geographies. For instance, improvement patterns might look different in developing country contexts with lower labor cost. Cross-country analyses could also assess spatial spillovers of experience and O&M cost reductions in an increasingly globalizing RE sector.⁴⁰ Finally, here, we studied the most deployed renewables (onshore wind and PV) only, but the dynamics of O&M costs are likely relevant for other new energy technologies as well. Examples worth analyzing include biomass combustion, concentrated solar power and offshore wind, where O&M costs can make up an even larger share of LCOE and thus could have the potential for major cost reductions with growing cumulative experience.

EXPERIMENTAL PROCEDURES

Research Case

We analyze onshore wind and PV as these are the two RE technologies that have grown the most over the last decade⁴⁴; they are also expected to contribute the

majority of new renewable capacity until 2040.⁴⁵ The analysis is limited to utility-scale plants, which we define for wind as horizontal axis turbines with a power rating starting at 100 kW and for PV as ground-mounted installations above 100 kW (smaller plants do not necessarily employ contracted O&M services).

Concerning regional scope, initial expert interviews (see below) strongly suggested that O&M costs are country specific and that their dynamics depend on the local market, such as different country markets in Europe (e.g., for onshore wind, Denmark, Germany, and the United Kingdom each had their own O&M market with local service companies during the study period). Major O&M cost differences are also visible in the limited available data.²¹ Thus, we focus our analysis on a single country, namely Germany, which was one of the earliest markets to adopt onshore wind and PV at the utility scale and between 2000 and 2017 added globally the most onshore wind capacity in 8 of 17 years and the most PV capacity in 13 of 17 years.⁸ We considered the period from 2000 on, when Germany enacted the landmark RE sources act, which also marked the beginning of a truly professionalized O&M industry according to exploratory expert interviews (in our data the first data point for wind operations is from 2000, for wind maintenance from 2004, and for PV O&M from 2005).

In this study, we consider experience and learning in onshore wind and utility-scale PV O&M on the *industry level* (as compared to experience and learning effects on the level of a specific firm only). Past empirical studies found for a number of industries (including shipbuilding, electronics manufacturing, and power plants)^{46,47} that experience effects lead to improvements in the entire industry, because “learning often cannot be kept entirely proprietary.”⁴⁸ Instead, horizontal spillovers across firm boundaries have been shown to be an important driver for industry-wide improvements, particularly in contexts where companies could not patent their innovations,⁴⁶ which is the case for many improvements in service industries like renewables O&M (a much-cited study on innovation in the service sector summarized “In almost every empirical study on service innovation, the protection of innovation activities is seen to be extremely difficult”⁴⁹). While the studies on other industries not necessarily predict that inter-firm spillovers play an important role for onshore wind and utility-scale PV O&M, our findings concerning improvement drivers strongly suggest the relevance of industry-level effects (compare main text and Figure S2): There are economies of scale on the industry level, e.g., achieved by higher density of plants, and there are efficiency gains in the entire industry, allowed for by specialized vocational trainings. Important cost reduction steps through learning by doing quickly became industry standard after individual plant owners and O&M service operators pioneered taking these steps, such as the reduction of scope and frequency of O&M services, and the modularization of O&M contracts (these innovations cannot be made proprietary). Finally, especially in the earlier years of onshore wind deployment, O&M learning by using and learning by interacting on the industry-level was encouraged by government intervention, such as via the mandatory technical incident reporting. In sum, the importance of inter-firm spillovers in the case of onshore wind and utility-scale PV supports the application of the experience curve concept for renewable energy O&M on the industry level, following the well-established practice for renewable energy capital cost and yielding experience rate estimates that can be applied in (industry-level) energy system models and integrated assessment models.

Quantitative Data and Analysis

The quantitative analysis is based on data we compiled from O&M contracts provided by interview participants (plant owners, O&M service providers, and technical and commercial asset managers—see below for details). Data were provided for this

study under the conditions (1) to be used for research only and (2) to be shown only in anonymized form and aggregated with data from other companies. For comparability, we sent a sheet to participants, which described the scope of services to be included in the cost figures (cf. [Table 1](#)); we also emphasized the importance of having a precise allocation of the respective price data to the year the contract was signed. In cases where data providers had several contracts that were signed in the same year, we used the average value across these contracts (which counts as one data point in our study). For wind, we also include archival information on community wind farms. For solar PV, 35% of the data points did not explicitly include vegetation management or green keeping, and the cost for this service has been added based on interviewee estimates. All data have been converted to EUR2017 using the German consumer price index CPI.⁵⁰ In total, we have 31 data points from 19 different data providers for wind maintenance, 30 data points from 18 different data providers for wind operations and 37 data points from 11 different data providers for solar PV. Summary statistics are provided in [Table S3](#).

For wind onshore maintenance and repairs, costs vary over the lifetime of turbines (the variance is much smaller for solar PV). In Germany, wind turbine machinery is initially covered by a two-year OEM guarantee (potentially spanning into three calendar years), which greatly reduces maintenance and repair cost. In the second decade of operations the costs often increase due to wear and tear. For clarity of analysis, we therefore focus on costs occurring in a well-specified interval of asset age, namely 4–8 years only, which was considered to be representative in the expert interviews. For 18 wind projects in the study, a full-time series of cost over 20 years of operations was available, which shows that the five-year period of asset age 4–8 exhibits flat costs (see [Figure S1](#)). According to these data, the year 4–8 interval overestimates year 1–20 O&M cost by 6%, making it a slightly conservative estimate for average lifecycle O&M cost.

Separately for wind maintenance, wind operations and solar PV, we estimate one-factor experience curves, as described in [Equations 1, 2, and 3](#), using data for cumulative energy produced in MWh from government statistics.⁵¹ Besides theoretical considerations, the choice of energy produced as the explanatory variable is also supported by insights from the expert interviews (see below), which stressed that experience in O&M is accumulated by operating and servicing assets (see discussion in the main text). For solar PV, only production from installations >100kW_p is considered (to exclude rooftop PV installations, which typically do not have formalized O&M contracts in Germany). We do not include R&D expenses as a separate factor (as has been suggested for technology cost learning curves)^{52,53} because service industries typically do not have R&D departments or conduct specific R&D investments.⁵⁴

We use ordinary least squares regressions in three different specifications (compare [Tables 1 and 2](#)) with uncorrelated but heteroscedasticity-robust standard errors (Model I), allowing for standard errors to be correlated between data points from the same data provider (“clustered,” Model II) and including control variables in addition to the explanatory variable (Model III). For the latter, we included only control variables that are independent from O&M experience, such as structural differences between plants (for wind—gearless versus geared turbines and whether community wind farm), and structural differences of the regulatory environment (for solar PV—introduction of auctions). To illustrate the importance of the explanatory variable, the supplementary data items also provide regression results for an alternative specification which uses cumulative installed capacity (MW) instead of cumulative energy produced (MWh) as explanatory variable (see [Table S6](#)).

Qualitative Data and Analysis

To assess the underlying drivers for O&M cost reduction, we followed an interview case study design.⁵⁵ First, explorative interviews were conducted with industry experts to discuss the case selection and to refine a questionnaire for subsequent in-depth interviews. Second, e-mail invitations for in-depth interviews were sent out to experts mentioned in public member lists of industry associations (esp. BWE advisory councils) or qualified to be knowledgeable by giving interviews in trade magazines, publishing reports, or speaking at relevant industry conferences. We also contacted industry associations BWE, Bundesverband Solarwirtschaft, SolarPower Europe, and Swissolar who referred us to further experts. Specific interviewee recruiting efforts were undertaken to ensure that the interview sample covered all relevant actors in the O&M industry (project developers, project investors and owners, O&M service providers, technical and commercial asset managers, utilities, OEMs, O&M software companies, and O&M consultancies). Following Eisenhardt's approach,⁵⁵ we continued holding interviews until no additional insights were observed. An anonymized list of interviewees is provided in [Table S5](#).

Interviewees were sent an interview guide in advance, which allowed them to prepare for the interview, see [Table S4](#). The interview guide provided background information on the research project and explained the questions, including detailed definitions of the scope of O&M services considered in the study. Interviews were held under the Chatham House rule, which states that "participants are free to use the information received, but neither the identity nor the affiliation of the speaker(s) [...] may be revealed." In total, 31 interviews were conducted between October 2017 and April 2018, with a duration between 40 and 120 min. Interviews were conducted in person or over the phone by one to three researchers, mostly in German. The discussions were recorded and transcribed verbatim; in the rare case that an interviewee did not consent to recording, the interviewers took detailed individual notes.

In addition to the interviews, 543 archival documents, such as O&M contracts, RE project investment prospectuses, industry reports, articles, webinars, and company newsletters were analyzed. The majority of these documents are public and were obtained through web research, though some documents (esp. contracts) were provided by expert interviewees with the requirement to be treated confidentially.

Interview transcripts and notes and important archival documents were analyzed using a software for computer-assisted qualitative analysis (MAXQDA). The analysis followed a systematic labeling of each statement containing improvements. Four types of codes were assigned: part of O&M that is improved by a specific driver (five options: O&M in general, maintenance and repairs, technical and commercial management, energy yield, and site management); background/type of driver (three options: technology-related drivers, market-related drivers, and drivers related to the internal processes of actors); year/period the driver applies to; and experience mechanism (compare [Box 1](#)). Finally, the long list of drivers was summarized to a text describing the most prevalent themes by two researchers for onshore wind and by two researchers for PV; the summaries were then integrated and cross-checked by the remaining two researchers. This procedure was chosen to ensure accurate and consistent summaries and to enhance confidence in the findings.⁵⁵

Projection of O&M Costs until 2030

Projections of O&M costs follow established methods for experience curve-based extrapolations.^{43,56} In order to apply the experience curves derived in this study, we draw on projected values for the explanatory variable (cumulative produced

electricity). To this end, we need to estimate annual capacity additions and plant retirement as well as capacity factors. For the capacity projections, we refer to the grid development plan (Netzentwicklungsplan)⁵⁷ for Germany. This is the official planning document for grid operators, signed-off by the German power grid regulation agency (Federal Network Agency for Electricity, Gas, Telecommunications, Post, and Railway). For both wind and solar PV electricity generation, we choose scenario C (scenario with high solar PV and onshore wind deployment), which projects 104.5 GWp cumulative installed solar PV capacity and 85.5 GW cumulative installed wind capacity by 2030. In lack of higher resolution data, we assume a linear increase in cumulative capacity from 2017 to 2030, which is in line with recent market developments (see Figure 4). For solar PV, we estimate the projected capacity larger than 100kWp by assuming its share of total solar PV deployment is the same as the average of the last ten years (52%). Capacity factors from 2017 are assumed to remain constant until 2030. When applying the derived experience curves, we use the point estimates from model specification I as well as the 95% confidence interval to produce the three curves presented in Figure 4.

To put our results into perspective, in Figure 4 we show values for projected O&M cost development through 2030 from other studies. To identify relevant sources, we refer to a summary of cost projections for power generation technologies by the DIW (German Institute for Economic Research),²³ which is widely used as a data source by German energy system models (e.g., models LIMES,²⁴ DIETER,⁵⁸ EMMA,⁵⁹ and dynELMOD⁶⁰).

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at <https://doi.org/10.1016/j.joule.2019.11.012>.

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AUTHOR CONTRIBUTIONS

B.S. designed the study with input from all authors; P.T., B.S., and M.B. conducted the expert interviews and qualitative and quantitative data analysis; and all authors interpreted the data and contributed to the final article.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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