Financial viability of grid-connected solar PV and wind power systems in Germany

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Abstract

The German electricity sector is in a period of transition, spurred by the German government’s endeavor to maintain a sustainable, secure, climate-friendly and affordable energy supply system. The most important aspects of this Energiewende are the phase out of nuclear energy, promotion of renewable energy technologies, and reduction of greenhouse gas (GHG) emissions. As a consequence, huge investments in power generation systems and infrastructure are needed. Wind and solar photovoltaics (PV) are important renewable energy sources for achieving the goals, but power generation depends on spatial and meteorological conditions on site. For new build PV systems, the level of on-site solar irradiation is crucial, whereas the yield of wind turbines is mainly determined by the wind speed on site. In the model-based analysis with the RETScreen software, we distinguish between three different regions in order to take differences in climatic and geographical conditions in Germany into account. For each region, six locations with specific site conditions are used for the calculations. Projections are made for the base year 2015 and the future year 2030. We find that PV systems achieve levelized cost of electricity (LCOE) below 11 €-ct/kWh in 2030, with a GHG reduction potential of 133-289 €/tCO\textsubscript{2}. The LCOE of wind power ranges from 5.1-16.1 €-ct/kWh and the related GHG mitigation costs from 101-321 €/tCO\textsubscript{2}. In light of these results, it seems to be possible to restructure the German electricity generation system in a cost-effective and environmentally efficient way. Due to decreasing unit investment costs and increasing capacity, solar PV and wind power become increasingly competitive against conventional power generation. Hence efforts are needed to enhance and optimize the grid integration of wind energy and PV and to maintain the long-term security of electricity supply during the transition process.

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1. Introduction

Primary energy consumption in Germany is highest in Europe (2014: 13,088 PJ), and well ahead of France and the United Kingdom, and is ranked as the world’s number seven [1]. Because of its limited domestic reserves, Germany is an energy-importing country. By counting nuclear as an imported energy source the total share of imported energy in the total primary energy supply was 70% in 2013 [2]. This leads to a dependency on exporting countries, which must be reduced by a wide-range diversification of supply sources [3]. Natural gas and crude oil completely depends on import from different countries. Petroleum has quantitatively the largest share in terms of energy consumption, followed by gas, and electricity. In 2013, 594.3 TWh of electricity were consumed in Germany. Renewable energy technologies have been increasing in recent years and provide a significant part of the domestic primary energy supply today [4, 2].

Total installed capacity in 2014 with all power plants was 195 GW in Germany [5]. Wind power and PV had the largest share, followed by natural gas, hard coal, lignite, oil, nuclear and water. The electricity generation technologies differ, thereby, in their availability and utilization hours. Conventional thermal power plants such as nuclear power, lignite, and hard coal, are characterized by a high number of utilization hours per annum. They have low variable costs and default rates. In contrast, wind power and solar PV depend on the weather and therefore show large fluctuations in their feed-in to the grid. Although wind power and solar PV accounted for 39.7% of the total installed capacity, they only generated 16% of the total energy demand in 2014 [5]. Nuclear, lignite, hard coal and gas jointly contributed 55% of the total generated electricity, despite their comparatively low installed capacity. However, due to the increasing share of renewable but fluctuant nature, thermal power plants are still indispensable for a stable energy supply today [6, 7].

In the context of GHG emissions, Germany is the largest emitter in the European Union. However, GHG emissions have declined since 2000. In the Energy Concept, the German Federal Government has established ambitious targets for GHG emissions reduction. In 2010, CO₂ emissions from fuel combustion accounted for the largest share of GHG emissions in Germany, with a total of 81.5%. More than 75% of CO₂ emissions by fuel combustion came from coal and oil usage (41.6% and 34.2%, respectively), in 2010 [8]. The power generation sector accounted for 43.4% of energy-related emissions in 2010 [9]. By considering the government’s targets and the price competitiveness along with the carbon mitigation potential, wind and PV are realistic options for future electricity generation.

Within the energy transition Germany pursues an ambitious target to switch from a leading industrialized nation to a sustainable, secure, climate-friendly, affordable, and nuclear power-free energy supply nation. Besides of the expansion of renewable energies and the increase in energy efficiency, energy-saving measures are important to mitigate climate change, save energy resources, and to boost Germany as a business location for sustainable and innovative development [5]. In general, Germany is on the way to achieve these ambitious goals. The expansion targets for renewable energy technologies have been fulfilled satisfactorily, however, at very high costs [10].

The basis for the development of renewable energies is the German Act on Granting Priority to Renewable Energy Sources (Erneuerbare Energien Gesetz, EEG). The rapid expansion led to a high share of renewables in German energy supply system, it can also increase the reallocation charge and then electricity prices. In order to reduce the costs for the further expansion of renewable energy the new Renewable Energy Sources Act focuses on less expensive technologies like wind energy and PV [5,6]. Based on this amendment, the share of renewable energy to be reached is up to 40-45% by 2025 and then to be raised further to 55-60% by 2035 [6].

In this paper, the techno-economic potentials of wind power and PV for different regions in Germany are determined. Thereafter, the power generation costs are estimated for the current year 2015. Expected future market prices are based on a literature review. Finally, associated CO₂ reduction costs are estimated and an assessment of the mitigation potentials carried out. The model-based computations are performed with RETScreen 4.0 (www.retscreen.net; cf. section 3.1). Overall, the present work includes an analysis of the role of grid-connected PV
and wind power generation in Germany by region, a financial analysis regarding the economic viability of the projects examined, as well as an analysis of the GHG emission mitigation potentials and a sensitivity analysis.

2. Methodology

2.1. RETScreen software

There are several models available for conducting a technical and financial viability analysis of potential energy projects. The Canadian RETScreen Clean Energy Project Software provides the analytical framework to estimate energy production, financial feasibility, GHG emission reductions potentials and costs [12]. RETScreen International is a clean-energy awareness, decision-support and capacity-building tool [13]. The core of the tool consists of standardized analysis that can be used to evaluate the energy production, life-cycle costs and GHG emission reductions for various types of renewable energy technologies (RETS). RETScreen uses a computerized system with integrated mathematical algorithms. The model uses a top to bottom approach. It provides a cost analysis, GHG emission reduction analysis, financial summary, and sensitivity analysis, and provides a low-cost preliminary assessment of RET projects. RETScreen requires less detailed information and less computational power. For instance, other models like HOMER, use hourly global solar radiation (GSR) levels for an entire year. That makes 8760 individual values in total, whereas RETScreen uses the monthly average GSR levels with only 12 values [14]. A comparison between RETScreen and more in-depth models using hourly values instead of monthly values showed that they produce roughly the same results, with an annual difference of less than 5% for projected energy production [15]. RETScreen convinces with adequate and comparable results, as well as integrated power plant and meteorological data. It has been already used for many countries and has a large user community.

The energy yield from a fictitious PV power plant is estimated using the annual average solar irradiation, temperature and humidity coefficients, inclination of the sun, and technical specifications such as efficiency and losses of the system. RETScreen then uses the energy estimation to determine the financial feasibility, and the GHG emission reduction prediction of the proposed project. Within the GHG analysis, RETScreen determines the annual GHG emission reduction for clean-energy technologies compared to a conventional technology base case. The results are given in terms of the amount of CO$_2$ that would be equivalent to the emission reduction. Methane and nitrous oxide emissions are converted into CO$_2$ equivalent emissions. The calculation itself is simple: the difference in the GHG emissions per unit of energy delivered is multiplied by the end-use energy delivered per year. RETScreen accounts for transmission and distribution losses as well [12].

RETScreen’s financial analysis accounts for the benefits of the electricity produced and the costs of the RET power plants. These estimates are then used to show financial statistics, such as the net present value (NPV), simple payback period (SPP), and internal rate of return (IRR) of the project. The cost estimate is made up of the initial costs, annual costs, periodic costs, and end-of-life costs. The financial analysis is the key element of the RETScreen model. Input parameters are the capacity, the energy exported to the grid, and the technology-specific mitigation potential for RET. LCOE and GHG emission mitigation costs are calculated as the final output value [13].

The sensitivity analysis provides an estimation of the sensitivity of important financial indicators – such as initial costs – in relation to key technical and financial parameters. RETScreen calculates the sensitivity of LCOE regarding initial and annual costs, debt ratio, discount rate, and debt interest rate.

2.2. Quantitative Framework

The competitiveness of RETs depends, in addition to the side-yield and finance parameters, on the initial and annual costs. It is now important to notice that these costs are only suitable for the German market. They differ globally due to various taxation systems, duties, or market developments. The project size has a significant impact on the investment costs due to scale effects. Usually, the larger the project, the lower the investment costs per kW. The cost assumptions for this work are based on a study by Fraunhofer-ISE and levelized cost of electricity (LCOE)
estimates [16]. The projection of the specific technology costs for 2030 are based on a learning curve model. Specifically, for solar PV a learning rate of 15% is assumed and for onshore wind 3%. The initial and annual operating and maintenance costs include end-of-life and periodic costs [16].

All costs specified in this study are related to real values of 2015. In an established facility, the average electricity production costs remain constant over the lifetime of the plants.

The yield of RET differ due to geographical differences in solar irradiation, wind speed, air pressure, ground temperature, and humidity. For PV systems, the solar irradiation is crucial. The yield of wind turbines is mainly determined by the wind speed at the respective location. Therefore, to take into account different climatic and geographic conditions of the different regions in Germany, the model is divided into three distinct regions. For every region, six locations with their specific conditions are chosen for the estimation.

- Region 1 (northern states of Germany) is defined by an average range of solar irradiation of 1100-1250 kWh/(m²a) and an average wind speed of 2-3 m/s
- Region 2 (mid-Germany) is defined by an average solar irradiation of 1050-1250 kWh/(m²a) and an average wind speed of 2-3 m/s.
- Region 3 (mainly Bavaria and Baden-Wuerttemberg) is defined by an average solar irradiation of 950-1050 kWh/(m²a) and an average wind speed of 4-5 m/s. [17]

Figure 1 illustrates the regional division of Germany adopted. The delamination lines are roughly approximated to the topography and the solar irradiation regions. Wind speed and solar irradiation are the key parameters for the respective locations. Humidity, air pressure, as well as the average ground temperature also have an impact on the yield of RET. Air pressure and temperature influence the air density, which in turn affects the energy transported by wind. Rising temperatures decrease the energy output of a PV system significantly, whereas humidity affects the life span.

In order to accurately predict the electricity generation from the solar module, RETScreen requires site-specific global solar irradiation values. RETScreen uses monthly average values for the calculations. For simplicity reasons, these are assumed to be constant over the years. Based on the historical data used [17], region 3 has the highest average solar irradiation throughout the year, followed by region 2, and region 1. The average monthly solar irradiation in Germany ranges between 160 kWh/m²/a (winter) and 1975 kWh/m²/a (summer), with only minor differences by region, whereas wind speeds range between 3.6-4.9 m/s (region 1) and 2.3-3.3 m/s (region 3). In contrast to the solar irradiation, average annual wind speed has its peak in winter and its minimum value in summer. The specific locations have been chosen in order to obtain the highest bandwidth of values in each region, thus covering the boundaries. Representative values for all 18 locations, including solar irradiation, wind speed, atmospheric pressure, average annual ground temperature, elevation, and humidity are considered. Within the energy model, the electric energy production fed to the grid and the capacity factor at each side is obtained using the meteorological and geographical data from the regions, respectively.
The PV system yield depends, in addition to the site conditions, on the sun’s angle on the surface, installed capacity, technology, and occurring losses, as explained above. Hence, three different sizes of PV systems are chosen for the estimation in RETScreen, i.e. roof-mounted small system (5 kWp), roof-mounted large system (200 kWp), and a ground-mounted large system (3000 kWp) using the following parametrization based on [18,19] (same for 2015 and 2030 unless indicated differently): lifespan 25 years, efficiency (mono-Si) 15% (2015 and 20% (2030), inclination angle 35°, performance ratio 85%.

The yield of onshore wind power plants basically depends on the hub height, the rotor diameter, the capacity, the wind speed, losses, and availability of the plant. For the estimation, a theoretical wind turbine is placed at the respective locations. Within, expected annual energy yield, the full-load hours and the average capacity factors are calculated. For the calculations, we use an Enercon E101 turbine, since this is a well-established model for low wind speed conditions in Germany. The parametrization for the onshore wind power system considered is as follows (based on [20,21], again, 2015 and 2030 values are the same unless specified differently): turbine capacity 3 MW, hub height 110 m (2015) and 130 (2030), rotor diameter 101 m, availability 98%, losses 10%, and windshear exponent 0.19.

Within a carbon analysis, the model calculates the annual GHG emission reductions for a clean energy project compared to a base case system. RETScreen has the necessary parameters already implemented. The baseline uses historical emission factors of fossil-fuelled power plants in Germany. The base case electricity system is estimated using inputs of the electricity sources mix by fuel type and baseline transmission and distribution (T&D) grid losses, respectively. The T&D losses are reported to be 2-8% [22]. RETScreen’s default emission factor for the base case systems is used in the analysis. The base case system contains all relevant fossil-fuelled power generation technologies. The emission factor for energy supply in Germany assumed is 0.501 t CO₂/MW h [22]. RETScreen compares this baseline GHG emission case with the proposed new electricity system. The PV system and the wind turbine do not emit GHG in this model. It is now important to note that the full lifecycle analysis does have GHG emissions from transportation, resource extraction, manufacturing, and more. However, the estimations in the model do not account for full lifecycle emissions of any of the conventional electricity supply, so the PV lifecycle emissions are also omitted.

For the financial analysis, RETScreen requires several assumptions for the initial and annual cost of PV systems and onshore wind (Table 1). Initial costs are given in terms of minimum and maximum price ranges for 2015 and 2030. The annual costs in 2015 and 2030 for roof-mounted small PV, roof-mounted large PV and ground-mounted PV are assumed at 35 €/kWp, those of onshore wind 0.018 €/kWh.

RETScreen requires assumptions for the debt ratio, the debt interest rate, the debt term, the inflation rate, and the discount rate. They differ depending on technology, plant size, and location. Hence, low project-specific risks (e.g. fixed feed-in tariff) and low requirements regarding the return on investment lead to low discount rates.

Table 2 provides a summary of the general assumptions made for the RETScreen calculations.

| Table 1. Initial costs assumed for solar PV and onshore wind [16, 22, 23] |
|-----------------|----------------|----------------|----------------|----------------|
|                  | Roof-mounted | Roof-mounted  | Ground-         | Onshore wind   |
| [€/kW]           | small PV     | large PV      | mounted PV      |                |
| Min / Max (2015)| 1300 / 1800  | 1000 / 1700   | 1000 / 1400     | 1000 / 1800    |
| Min / Max (2030)| 800 / 1000   | 570 / 950     | 570 / 800       | 950 / 1700     |

| Table 2. Parametrization for the financial analysis in RETScreen [12, 23] |
|----------------|----------------|----------------|----------------|----------------|
| Parameter      | Roof-mounted | Roof-mounted  | Ground-         | Onshore wind   |
|                | small PV     | large PV      | mounted PV      |                |
| Debt ratio (%) | 80            | 80            | 80             | 70             |
| Debt interest rate (%) | 4          | 4             | 4              | 4.5            |
| Debt term (a)  | 20            | 20            | 20             | 20             |
3. Results and discussion

After taking into account all assumptions and parameters mentioned in the previous section, the RETScreen model is run. The results include the PV system and onshore wind energy yield, as well as the GHG emission reduction potentials by RET, the LCOE, and the GHG emission mitigation costs for different regions in Germany. The subsequent sensitivity analysis also includes the respective capacity, electricity generation, and the mitigated GHG emissions. Note that PV systems only differ in their capacity, size, cost, and finance structure, whereas the technology, inclination of the sun, losses and site conditions are assumed to be the same. Therefore, the yields of the PV systems are identical for the different regions. The values are to be understood as the yearly average net values for PV systems over 25 years, and onshore wind over 20 years of operation.

3.1. Capacity, electricity generation, and carbon analysis

The average installed capacity for PV systems and onshore wind power plants for 2015 and 2030 is shown in Fig. 2(a). It shows that wind has a significantly higher capacity than PV systems in regions 2 and 3. PV systems have the highest (lowest) capacity in the south (north) with 13.15% and 10.9%, respectively. Conversely, wind has the highest (lowest) capacity in the north (south) with 30.5% and 11.5%, respectively. According to Fig. 2, installed capacities are generally higher in 2030 than in 2015. PV systems have, on average, a 5.5% higher capacity in 2030 than in 2015. The capacity of onshore wind increases by about 6.14% on average from 2015 until 2030.

The average yearly electricity generation of RET in MWh/(MW a) of installed capacity is shown in Fig. 2(b) Electric generation of PV systems is significantly higher in region 3 (1.15 MWh/MW) than in region 1 (0.96 MWh/MW). In turn, electricity generation of onshore wind power plants has the highest values in region 1 (2.67 MWh/MW) and decreases to region 3 (0.93 MWh/MW). The electricity generation in 2030 is higher than in 2015. PV systems have on average 5.5% higher electricity generation in 2030 compared to 2015, while onshore wind increases by about 6.14% on average.

![Fig. 2.](image-url)

Fig. 2. (a) Capacity (%); (b) electricity generation (MWh/MW/year); (c) specific emission mitigation means (in t CO2/MWa) of RETs installed, by region, 2015 vs. 2030.
Within a carbon analysis, RETScreen also allows to calculate the reduction of GHG emissions as a result of using wind and solar PV as electricity generation sources. The resulting GHG emission mitigation per MWa of the respective RET for all regions in 2015 and 2030 are presented in Fig. 2(c) (the unit t CO₂/MWa denotes that one MW of installed capacity of a respective RET reduces CO₂ emissions by a specific amount per year). For 2015, wind energy has the highest GHG mitigation potential in region 1 (1300 t CO₂/MWa). PV systems in region 1 and wind energy in region 3 have the lowest potential (500 t CO₂/MWa). A PV system installed in region 3 has an 18% higher GHG mitigation potential than in region 1. In contrary, wind energy in region 3 has a 277% lower GHG mitigation potential than in region 1. In 2030, GHG potentials of all regions increase by 5.9% on average. In terms of the projects analyzed, this implies that a 3 MW wind turbine would on average mitigate 3789 t CO₂ per year in region 1 and 1404 t CO₂ in region 3. A fictitious 3 MW open-grounded PV system, in contrast, would in 2015 reduce, on average, 1731 t of CO₂ emissions per year in region 3, and by 1441 t CO₂ per year in region 1. In 2030, the GHG reduction potential for a theoretical 3 MW wind turbine would increase on average by up to 4016 t CO₂ in region 1, and by 1515 t CO₂ in region 3, whereas a fictitious 3 MW open-grounded PV system would in 2030 help to mitigate on average 1833 t CO₂ in region 3 and 1617 t CO₂ in region 1.

3.2. Financial analysis: LCOE

In this section, the results of LCOE in 2015 and 2030 are presented for PV system types and onshore wind power plants. Fig. 3(a) shows the LCOE for small roof-mounted PV-systems in different regions in Germany for 2015 and 2030. For 2015, the highest values appear for region 1 with 13.4-16.8 €-ct/kWh, and the lowest in region 3 with 11.2-14.0 €-ct/kWh. The LCOE in region 1 is on average 2.5 €-cents higher than in region 3. The LCOE decreases significantly in 2030. Thus, the LCOE of region 1 in 2030 is on average 5 €-ct lower than in 2015. The LCOE in 2030 is below 11 €-ct/kWh for all regions. Region 3 has the lowest LCOE values (7.9-8.9 €-ct/kWh), while in region 1 they are highest (9.4-10.7 €-ct/kWh). In 2030, the LCOE in region 3 are, on average, 1.7 €-ct lower than in region 1, and 1.0 €-ct lower than in region 2.

Fig. 3(b) shows the LCOE for large roof-mounted PV systems in different regions in Germany for 2015 and 2030. For 2015, the highest values appear for region 1 (11.4-16.2 €-ct/kWh), and the lowest in region 3 (9.5-13.5 €-ct/kWh). In 2015, the LCOE of region 1 are on average 2.3 €-ct higher than in region 3. The LCOE of large roof-mounted PV systems decreases significantly in 2030. The LCOE is below 11 €-ct/kWh in all regions. In 2030, the lowest LCOE are found for region 3 with 6.6-8.7 €-ct/kWh, and the highest in region 1 with 8.0-10.5 €-ct/kWh. The
LCOE of region 1 in 2030 is, on average, 1.5 €-cents higher than in region 3. The LCOE of region 1 in 2030 is on average 4.6 €-cents lower than in 2015.

Fig. 3(c) shows the LCOE for open-grounded PV systems in different regions in Germany for 2015 and 2030. For 2015, the highest values appear for region 1 (11.4-14.2 ct/kWh) and the lowest in region 3 (9.5 - 11.8 €-ct/kWh). The LCOE of region 1 in 2015 is, on average, 2.1 €-ct higher than for region 3.

The LCOE of ground-mounted PV systems decreases significantly in 2030. Thus, the LCOE of region 1 is on average 4.1 €-ct lower than in 2015. Region 3 has the lowest LCOE in 2030 (6.7-7.9 €-ct/kWh), whereas region 1 has the highest LCOE (8.0-9.5 €-ct/kWh). Note that all values in 2030 are below by 10 €-ct/kWh. The LCOE in 2030 in region 1 is, on average, 1.5 €-ct higher than in region 3.

Fig. 3(d) shows the LCOE of onshore wind in 2015 and 2030 for different regions in Germany. For 2015, the LCOE of onshore wind lies between 5.9-7.9 €-ct/kWh in region 1 and 7.1-18 €-ct/kWh in region 3. Notice that the LCOE in region 3 is, on average, 7.8 €-ct higher than in region 1, and that of region 2 on average 2.0 €-ct higher than in region 1.

The LCOE of onshore wind energy in Germany decreases modestly in 2030. Thus, the LCOE of region 1 is on average 0.5 €-ct lower than in 2015. Region 3 has the highest LCOE in 2030 (9.9-16.1 €-ct/kWh), while region 1 has the lowest ones (5.1-7.4 €-ct/kWh). The values of regions 1 and 2 in 2030 are both below 10 €-ct/kWh. The LCOE in 2030 in region 3 is, on average, 6.8 €-ct higher than in region 1, and 1.8 €-ct higher than for region 2.

3.3. Greenhouse reduction costs (GRC)

In this section, results for GHG reduction costs for RET in different regions for 2015 and 2030 are presented. Herein, the results are given in ranges, as explained in the methodology section. It represents the cost of avoiding one ton of CO₂ emitted by the average German electricity production system.

Fig. 4(a) shows the GHG reduction costs for small roof-mounted PV systems in the three regions. In 2015, GRC ranges between 222-334 €/t CO₂ in region 3 and region 1, respectively. Region 3 has on average 50 €/t CO₂ lower GRC than region 1. The GRC in region 2 is on average 33 €/t CO₂ lower than in region 1. The GHG reduction cost decrease significantly in 2030. The GRC in region 3 is on average 84 €/t CO₂ lower in 2030 than in 2015 (minimum: 156 €/t CO₂, maximum 214 €/t CO₂).

Fig. 4(b) shows the GHG reduction costs for large PV roof-mounted systems in different regions in Germany for 2015 and 2030. In 2015, GRC range between 190-324 €/t CO₂ in region 3 and region 1, respectively. Region 3 has
on average lower GRC of 46 €/t CO\(_2\) than region 1, and on average lower GRC of 30 €/t CO\(_2\) than region 2. Also here the GHG reduction costs decrease significantly in 2030. The GRC in region 3 are on average 76 €/t CO\(_2\) lower in 2030 than in 2015 (minimum: 133 €/t CO\(_2\), maximum: 209 €/t CO\(_2\)).

Fig. 4(c) shows the GHG reduction costs for open-grounded PV systems in different regions in Germany for 2015 and 2030. In 2015, the GRC range between 190-283 €/t CO\(_2\) in region 3 and region 1, respectively. Region 3 has, on average, 42 €/t CO\(_2\) lower GRC than region 1, and on average a lower GRC of 28 €/t CO\(_2\) than region 2. Again, the GHG reduction costs decrease significantly in 2030. The GRC in region 3 are on average 67 €/t CO\(_2\) lower in 2030 than in 2015 (min: 133 €/t CO\(_2\), max: 289 €/t CO\(_2\)).

Fig. 4(d) shows the GHG reduction costs for onshore wind energy in the three regions considered. In 2015, the GRC ranges between 108-360 €/t CO\(_2\) in regions 3 and 1, respectively. Region 1 has, on average, a lower GRC of 156 €/t CO\(_2\) than region 3, and on average a lower GRC of 40 €/t CO\(_2\) than region 2. The GHG reduction costs slightly decrease in 2030 (in region 3, they are on average 10 €/t CO\(_2\) lower in 2030 compared to the 2015 value; min: 101 €/t CO\(_2\), max: 321 €/t CO\(_2\)).

3.4. Sensitivity analysis

This section describes the results of the sensitivity analysis. The parameters considered are initial and annual costs, debt ratio, discount rate, and debt interest rate.

Fig. 5(a) shows the impact of variations of the key parameter values on the LCOE of PV systems. The sensitivity analysis is done for a small roof-mounted PV system. Heidelberg was chosen as location with a yearly average solar irradiation value of 1150 kWh/ (m²a). Initial costs of 1500 €/kW\(_p\) were used. A deviation in initial costs causes a very large change in the LCOE, followed by the annual costs. In contrast, discount rate, debt rate, and debt ratio all have only a low impact on the LCOE. Fig. 5(b) shows the impact of varying key parameter values on the LCOE of onshore wind energy. The sensitivity analysis shown was computed for the location of Chemnitz, assuming an average annual wind speed of 4.2 m/s and 1400 €/kW of up-front investment costs. The largest impact on the LCOE of onshore wind comes from the initial investment costs. In contrast, financial parameters are found to have a comparatively little effect on LCOE.

3.5. Discussion of the results

The LCOE and GRC vary regarding the technology and the specific site conditions. They decrease from 2015 to 2030 due to the technology enhancements and a drop of their system prices. Generally, the site conditions for wind are more favorable in region 1 than in regions 2 and 3. This leads to comparably higher wind yields and larger GHG reduction potentials in region 1. The site conditions for PV systems are, contrary to onshore wind, most suitable in region 3, followed by regions 2 and 1. For that reason, the solar yield and GHG reduction potentials for PV systems are greatest in region 3. Capacity and net electricity generation are increasing for both technologies from 2015 to 2030. This is due to higher efficiency of PV systems and larger hub heights of onshore wind power plants. Wind energy has a comparably higher yield than solar PV. Electricity generated by onshore wind power plants in region 1 is more than twice as large as the maximum of electricity generation by PV systems. The same applies to GHG
emission reduction. Therefore, the site conditions for onshore wind in regions 1 and 2 offer the best environment from the point of view of techno-economic feasibility and GHG reduction, followed by the site conditions for PV systems in regions 2 and 3.

In 2015, onshore wind energy in region 1 features the lowest estimated LCOE (5.4-8.0 €-ct/kWh), followed by PV systems in region 3 with LCOE of 9.5-14.0 €-ct/kWh. The highest LCOE is found for onshore wind energy in region 3 (11.0-18.1 €-ct/kWh). Large open-grounded PV systems have the lowest and small roof-mounted PV systems the highest LCOE amongst the solar PV systems considered. The GRC vary between 108 and 360 €/t CO₂, depending on technology and site conditions. Onshore wind energy in region 1 are found to have the lowest GRC (108-160 €/t CO₂), whereas the highest occur in region 3 (220-360 €/t CO₂). Open-grounded PV systems feature the lowest GRC of all PV systems investigated, with values ranging from 190-235 €/t CO₂ in region 3.

In 2030, onshore wind energy in region 1 appears to have the lowest LCOE with 5.1-7.4 €-ct/kWh. Due to higher learning rates, PV systems are about to close the gap. In each region, the LCOE of PV systems are below 11 €-ct/kWh. The LCOE of region 1 is on average 5 €-cents lower in 2030 than in 2015. Large open-grounded PV systems have the lowest LCOE. Nevertheless, small roof-mounted PV systems are becoming increasingly competitive. Onshore wind energy has the lowest GHG reduction costs in region 1. Small roof-mounted PV systems have the largest potential. The GRC in region 3 of small roof-mounted PV systems are on average 84 €/t CO₂ lower in 2030 than in 2015. This is a 9.5 % decrease compared to large roof-mounted PV systems and a 20% decrease compared to open-grounded PV systems.

Finally, the sensitivity analysis for small roof-mounted PV systems in Germany shows the strong dependence of the LCOE on the initial costs. This explains the sharp drop of LCOE during the last years due to the drop of module prices. The sensitivity analysis undertaken for onshore wind energy shows similar results. However, the learning rate of wind is comparatively low. Therefore, system prices do not show such a marked drop as it is found for PV systems module prices. The estimated values for LCOE of onshore wind energy in 2015 and 2030 matches with the presented results of other studies. The results of roof-mounted PV systems are on average 0.8 €-ct higher. The calculated values of open-grounded PV systems are 2.5 €-ct above the average results of the presented studies. The reasons for these differences are different assumptions made for the energy model, such as module efficiency, sun tracking systems, system size, and meteorological assumptions.

4. Conclusions

In general, our study shows that it is possible to achieve the ambitious goals of Germany’s Energiewende. Decreasing electricity production costs of RETs, as well as the rising costs of fossil-fueled power plants strengthen the RETs’ competitiveness. In the long term, this will reduce the costs for Germany’s electricity generation system and help to avoid large amounts of GHG emissions. In order to shed some new light on this transition process, the LCOE and GRC have been estimated for different regions in Germany for current and prospective technologies, also taking into account their system prices. Specifically, the expected yield, capacity, and GHG mitigation potential for small- and large-scale roof-mounted and ground-mounted PV systems and for onshore wind power plants have been calculated for different locations. Furthermore, the LCOE and the GHG reduction costs have been assessed, and the LCOE has been reviewed in terms of their sensitivity regarding to changes in the values of various key parameters.

The results show that electricity generation costs of wind turbines will decrease only slightly in the future. The capacity will increase through technical improvements and result in higher GHG reduction potentials. The future GHG emission reduction costs of the RETs studied are found to range from 101-321 €/kWh. The electricity generation costs of PV systems will fall significantly in the future. The decline in prices of PV systems will make them competitive against fossil-fuel-based power generation systems in the near future, even in the absence of subsidies. Specifically, in 2030, the LCOE of PV falls below 11 €-ct/kWh. The future GHG emission reduction costs for PV range between 133-289 €/t CO₂. Roof-mounted systems are found to have the greatest cost reduction potential, with an average decrease that is 84 €/t CO₂ lower in 2030 than in 2015.

In the future, primarily the site conditions will determine whether or not wind power plants are more cost-effective than PV systems. In northern Germany, wind power has significantly higher yields and, therefore, lower
GHG emission mitigation costs. Open-grounded PV systems have the lowest LCOE and GHG reduction costs among PV systems. However, roof-mounted systems become more important due to their high expansion and GHG reduction potentials. The yield of the PV systems considered does not vary much for the different regions compared to onshore wind. Based on the results from our study, we conclude that it is possible to restructure the German energy generation system both cost-effectively and environmentally efficient. Solar PV and wind energy are already or becoming cost-competitive vis-à-vis fossil electricity generation sources due to decreasing investment costs and increasing capacity. However, further research must be undertaken in order to optimize the integration of wind and solar PV into the electric grid. This includes the economic analysis of grid expansion, storage systems, as well as fossil-fueled power plants with enhanced flexibility [6, 16].

References