Cost Optimal Expansion of Renewables in Germany

A comparison of strategies for expanding
wind and solar power in Germany

STUDY

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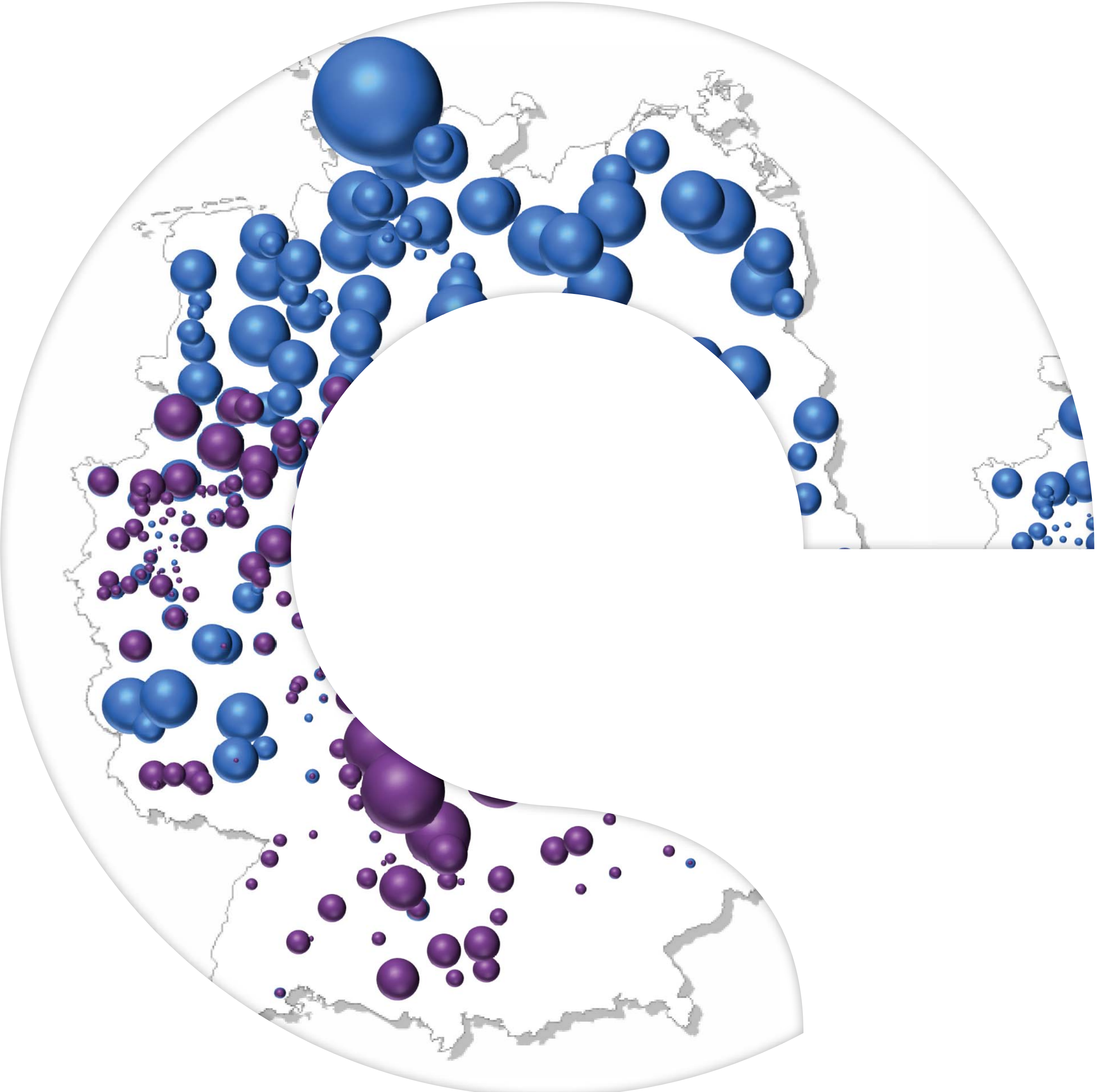

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STUDY SUMMARY

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A comparison of strategies for expanding wind and solar power in Germany

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CONSULTATIVE GROUP

We would like to thank the members of the consultative group for their input. The responsibility for the results lies exclusively with Agora Energiewende and the institutes involved.

The consultative group included representatives of:

- The German Ministry of the Environment, Nature Protection, and Reactor Safety,
- The Bavarian Ministry of the Environment and Health,
- The Ministry of the Environment, Climate, and Energy Sector Baden-Württemberg,
- The Ministry of Economics, Energy, Industry, Mittelstand and Trade in North Rhine-Westphalia,
- The Ministry of the Energiewende, Agriculture, the Environment, and Rural Areas Schleswig-Holstein.

Preface

Dear readers,

Germany's energy transition has to be affordable. In view of the continuing expansion of renewables, a number of questions arise that are crucial for future costs of our power system:

- Where should wind turbines and solar arrays be built – in the best sites or close to consumers?
- Does the expansion of renewables have to wait for grid expansion?
- What will happen if PV arrays with battery storage breakthrough on the market, and will we still need grids?

Agora Energiewende had Consentec look into these questions with the support of Fraunhofer IWES.

A number of scenarios were investigated up to 2033 based on the German Network Agency's lead scenario for the Grid Development Plan 2013. In addition to the cost of renewable energy, the cost of grids, storage, and conventional power generation was taken into consideration.

The findings are quite interesting and offer some new and surprising insights even for experts. To facilitate further discussion, the assumptions used are published on Agora Energiewende's website.

I hope you enjoy the read!

Best regards,
Rainer Baake
Director Agora Energiewende

The results at a glance

1. **Policy makers have a large scope of action in designing policies for the regional distribution of onshore wind and photovoltaics.**
   Regional distribution of this renewable energy has little impact on the total cost of power supply.

2. **Finding the right balance is important in expanding offshore wind power.**
   To promote technology development and reduce the cost of electricity for consumers, expansion should be continued, but on a lower level than current plans foresee.

3. **Grid expansion is an important prerequisite for the Energiewende.**
   Solely in terms of cost, a few years of delays for the additional transmission lines foreseen in the German Grid Development Planning act would not be critical. Further expansion of renewables does not have to wait for these new transmission lines.

4. **A strong focus on battery storage systems combined with photovoltaic is currently not desirable.**
   Only if cost of such systems drop by 80 % in the next 20 years would a renewable expansion path focusing on photovoltaics + storage be an economically viable option.

Contents

1. Question and Approach of the Study

Should wind turbines and solar arrays be primarily built in locations with the best wind and solar conditions or close to where power is consumed?

This question is a subject of controversy in the current discussion about the further expansion of renewables in Germany. There are two opposed camps. The first argues that wind turbines and solar arrays should be built in areas where the conditions are the best suited for them – which means northern Germany for wind turbines and southern Germany for solar arrays. Power can thus be produced at the lowest cost. The other camp counters that solar and wind should be built all over Germany, and especially in areas close to where the most power is consumed in order to reduce the cost of grid expansion and storage. To date, no such study comparing the two options in their entirety and in detail has been published.

The total system cost of the power supply is decisive – not only the direct cost of renewables, but also the indirect cost of grids and effects on the power system

To answer the aforementioned question, Agora Energiewende asked the consulting firm Consentec to investigate the effects of different optimization strategies on the total system cost of power supply. In addition to the cost of renewable power generation, the costs of transmission and distribution grids are taken into account, as well as indirect effects on cost of residual power generation. The study considers not only power supply in Germany, but also the market-driven trading and dispatch of the European power system. Fraunhofer IWES simulated the feed-in of wind and solar power in detail across time (8,760 hours a year) and space (over 360 grid nodes in Germany) based on historical weather data.

The study's starting point is the reference scenario of the German regulator for the Grid Development Plan 2013, which was then compared with alternative scenarios

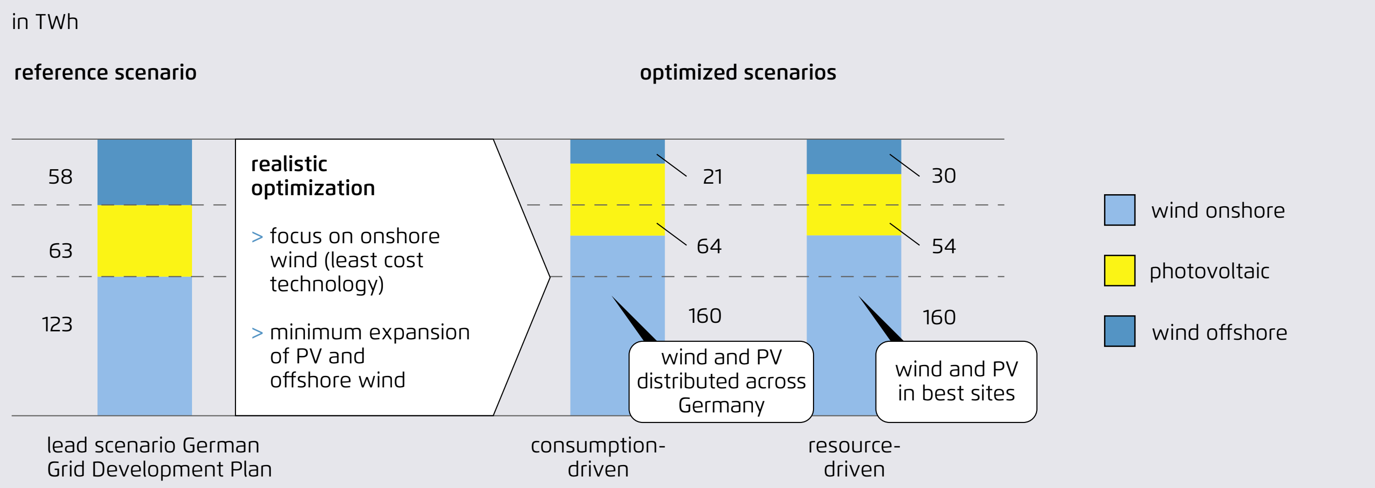
The study builds on the scenario framework for the German Grid Development Plan 2013, which was approved by the German regulator (*Bundesnetzagentur*). The reference scenario used in the study therefore contains the forecast for the expansion of wind and solar power until 2023 and 2033 in Germany[1] approved by the German regulator. Two alternative scenarios of renewable expansion were then defined and compared to the reference scenario: the first, focusing on renewable power generated close to consumers ("consumption-driven"); and the second, focusing on renewable power generated in the best locations ("resource-driven"). The scenarios are designed in such a way that the sum of the renewable electricity produced (measured in terawatt-hours before curtailment) is equal, requiring different capacities (in gigawatts, GW) because of the different technologies used and locations chosen in the scenarios. A minimum expansion for both photovoltaics and offshore wind is taken for granted to produce politically realistic optimization scenarios, not theoretical extremes.[2]

The consumption-driven scenario has considerably less electricity from offshore wind turbines than the reference scenario because offshore wind power is generated far from consumers. Instead, more wind power comes from onshore turbines and slightly more from photovoltaics. In addition, the expansion of wind turbines and solar arrays is more spread out across all of Germany in the consumption-driven scenario than in the reference scenario, which contains a

1 Scenario B of the Grid Development Plan is used here, which is considered the most likely scenario of the three scenarios used for grid planning in Germany.

2 For photovoltaics, at least 52 GW in 2023 and 2033; for offshore wind at least 5 GW in 2023 and 9 GW in 2033.

Power generation from wind and solar in the scenarios in 2023 — Figure 1.1



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concentration of wind power in the north and photovoltaics in the south.

The resource-driven scenario focuses on the least cost per kilowatt hour of renewable electricity. Consequently, generation from both offshore wind and photovoltaics is reduced compared to the reference scenario, with the least expensive technology – onshore wind – playing a greater role. The placement of additional wind turbines in this scenario focuses on the best locations in northern Germany.

Does the expansion of renewables have to wait for the expansion of the grid?

When a lot of wind is blowing in northern Germany, already today wind turbine generation is curtailed in certain instances because insufficient grid capacity is available to transport the high volume of power. Yet no detailed systematic study has been conducted on whether – and to what extent – delays in grid expansion impact the total cost of the power supply. This study investigates this question, particularly to find out whether a delay in grid expansion leads to a different evaluation of the optimized growth paths. To this end, the total cost of power supply was calculated in two versions of each optimized growth path: first, assuming that grid expansion is delayed by around ten years;[3] and second assuming that the grid is expanded quickly and completely, according to the requirements of the respective renewable growth path. The total cost was then compared to those of the reference scenario in which renewable expansion is based on the forecast of the German regulator and assuming that grid expansion is delayed around ten years.[4]

What happens when everyone starts getting their own power from solar arrays with battery storage?

Already, feed-in tariffs for newly installed PV arrays are far below the retail power rate. The difference is the result of

3 In the "delayed-grid scenario", the starting grid of the German Grid Development Plan (mainly, the lines in the Electricity Grid Expansion Act (*Energieleitungsausbaugesetz*, EnLAG)) are assumed to be completed by 2023; for 2033 it is assumed that the measures included in the current draft of the grid expansion law (*Bundesbedarfsplangesetz*), which are foreseen to be implemented by 2022, are completed, yet with a ten year delay.

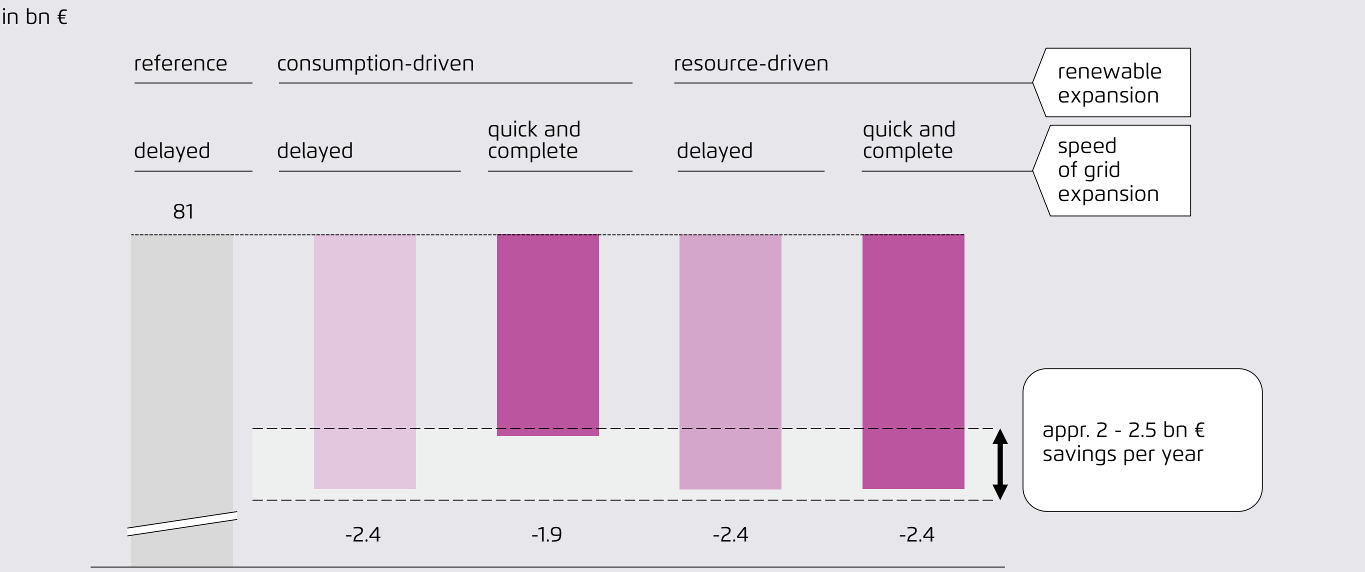
4 A scenario with a growth path of renewables according to the German regulator's lead scenario and at the same time a quick and complete grid expansion was not considered, as this is calculated in detail by the German transmission grid operators and would be an unnecessary duplication of analysis.

taxes, levies and other charges. It therefore pays to directly consume the power produced by your own PV array. One obstacle towards that goal is the time difference between power production and consumption. Direct consumption can increase if distributed storage systems are used. The technical and financial effects of a massive rollout of PV arrays with battery storage have not yet been studied for Germany.

This study therefore investigated a scenario in which Germany has 150 GW of photovoltaics with 40 GW of battery storage by 2033. The focus of this additional investigation was not on analyzing the total cost of power supply, which would be pure speculation in such a PV + battery breakthrough scenario anyway. Rather, we try to find out what the cost of such systems would have to be for the total cost of power supply to be comparable with the prices in other scenarios.

2. Results

Total annual cost of power supply and savings compared to reference scenario in 2023 Figure 2.1



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1. In 2023, an optimized expansion of wind and solar power in Germany could save around two billion euros a year

The analysis of the total cost of power supply shows that in all optimized expansion paths considered, the costs are considerably below the level of the reference scenario.[5] The annual savings in 2023 vary – depending on the scenario – from 1.9 to 2.5 billion euros.[6]

These figures include differences in the cost of renewables and transmission and distribution grids, as well as the different utilization of remaining power plants.

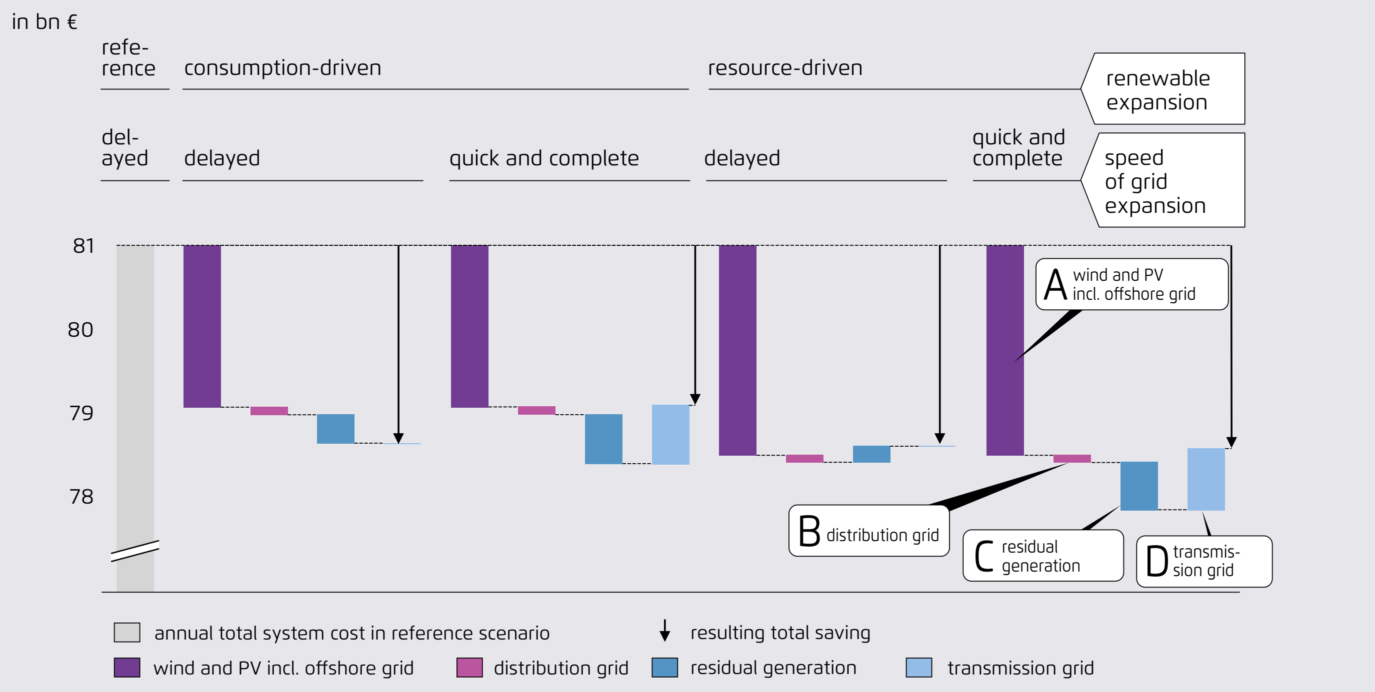
The major cost reduction lies in focusing the expansion of wind power onshore instead of offshore

The main cost reduction in the optimized expansion paths comes from the lower investment costs of renewables (savings of 1.9 to 2.5 billion euros, labeled A in the chart on the next page). There is considerable optimization potential here because of the high assumptions in the Grid Development Plan's reference scenario for offshore wind (14 GW compared to the current 0.3 GW). In both optimized expansion paths, a lot of onshore wind replaces offshore wind power. Because of the lower power production per installed capacity (a lower capacity factor), more wind turbines are needed onshore than offshore. Yet due to the great difference in investment costs (per GW) the total investment

5 The reference scenario includes the growth path of renewables in the lead scenario of the German Grid Development Plan and the assumption of a ten year delay in grid expansion.

6 Equivalent to two to three percent in terms of the total cost of power supply in 2023. The total cost of power supply in the reference scenario for 2023 is estimated at around 81 billion euros, including annuities for the capital costs of existing power plants, grids, renewable capacities, variable costs, and fuel costs for both fossil and renewable energy.

Differences in cost of scenarios compared to reference scenario Figure 2.2



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costs are significantly lower in the end.[7] This great difference in total investment cost between offshore and onshore wind is much larger than the difference in investment costs between the scenario with additional wind onshore in the north and the scenario with additional wind onshore in the interior (more installed capacity is needed in the interior for the same amount of electricity).

Indirect effects on the power supply system have only a relatively small impact on the total system cost in 2023

The impact of the sum of indirect effects of different growth paths for renewables on the cost of the rest of the power supply is low compared to the differences in investment costs for renewables. Three principal indirect effects were studied in detail:

→ Different cost of expanding the distribution grid (savings of around 0.1 billion euros in both scenarios, labeled B in the chart above), driven by different amounts of renewable capacities that need to be connected at different levels of the grid.[8]

→ Different cost to provide residual (conventional) power, including replacing curtailed energy (around -0.6 to +0.2 billion euros, labeled C in the chart), driven by different production patterns of different renewables in different locations (more constant feed-in of wind offshore, photovoltaic feed-in correlated with daily consumption patterns, time-staggered feed-in of wind onshore in the south) and by different speeds of grid expansion.

7 The results suggest that a similar result can be expected if onshore wind power replaces power from photovoltaics. However, there is little optimization potential in light of the relatively small difference between the assumptions on the growth of photovoltaics in the reference scenario (61 GW compared to around 32 today) and the minimum assumed expansion of 52 GW.

8 All voltage levels of distribution grids where considered, including low, medium, and high voltage.

- → Different cost of expanding the transmission grid only in those scenarios with a quick and complete grid expansion (around +0.7 billion euros, labeled D in the chart), driven by different renewables expansion paths.

2. An optimization toward a consumption-driven renewable expansion leads to roughly the same savings as optimization toward a resource-driven expansion

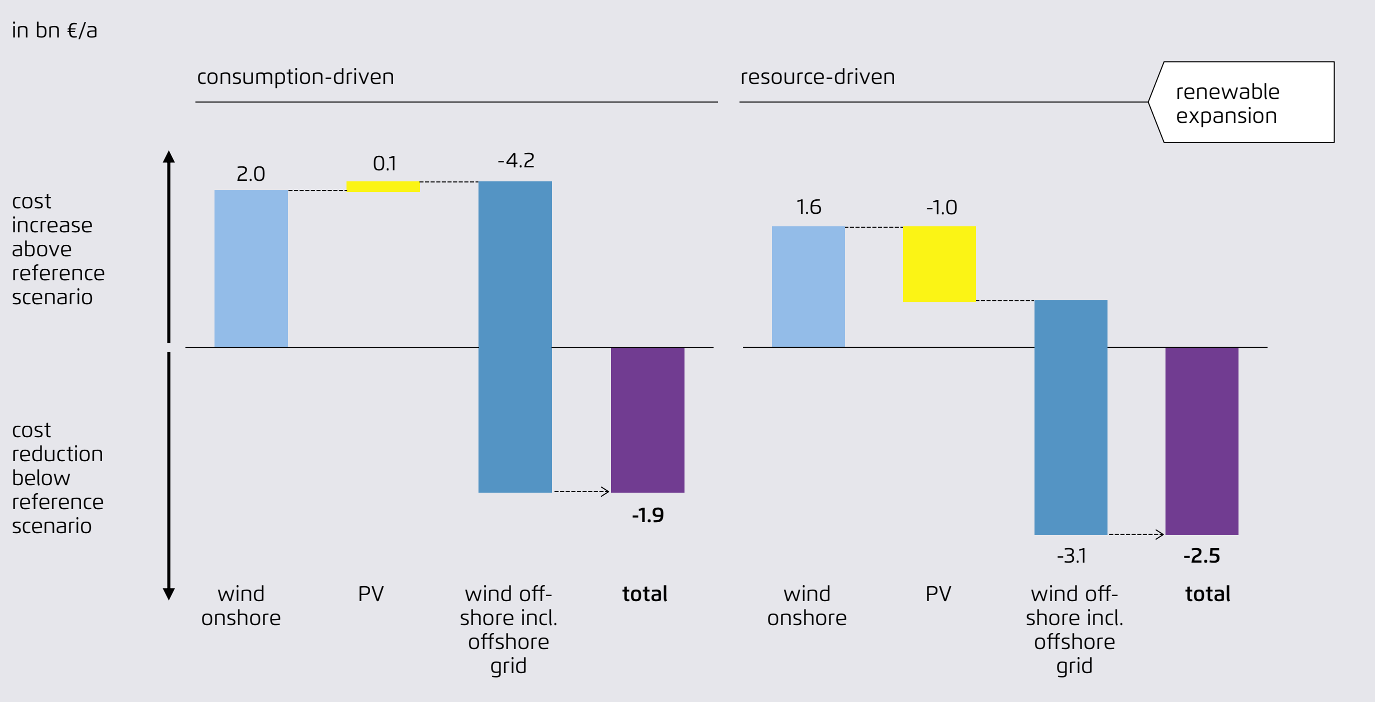
The two optimization strategies analyzed lead roughly to the same cost reductions relative to the reference scenario. When optimization focuses on a resource-driven expansion, around 0.1 billion euros more a year can be saved than when the focus is on consumption-driven expansion. This surprising finding is the result of two opposite effects that roughly compensate for each other in the scenarios. In the resource-driven scenario, investment costs for renewables are roughly 0.6 billion euros a year lower than in the consumption-driven scenario (less renewable capacity is needed as better-quality sites are used). On the other hand, the indirect effects in the consumption-driven scenario lead to savings of around 0.5 billion euros compared to the resource-driven scenario (mostly less renewable curtailment).

Investment cost for renewables are lower in the resource-driven scenario

The larger savings in the resource-driven scenario are mainly driven by the lower investment costs for onshore wind power. In the optimization strategy, wind turbines are built in the best locations (in the north of Germany). In the consumption-driven scenario, lower-quality wind sites are used; so to produce the same amount of power from onshore turbines, a larger number of more expensive wind turbines[9] is needed (roughly 20 percent greater installed capacity).

9 In line with recent developments, the study assumes that wind turbines built in lower-quality sites are higher and thus more expensive.

Differences in investment cost of wind and PV plants, 2023 — Figure 2.3



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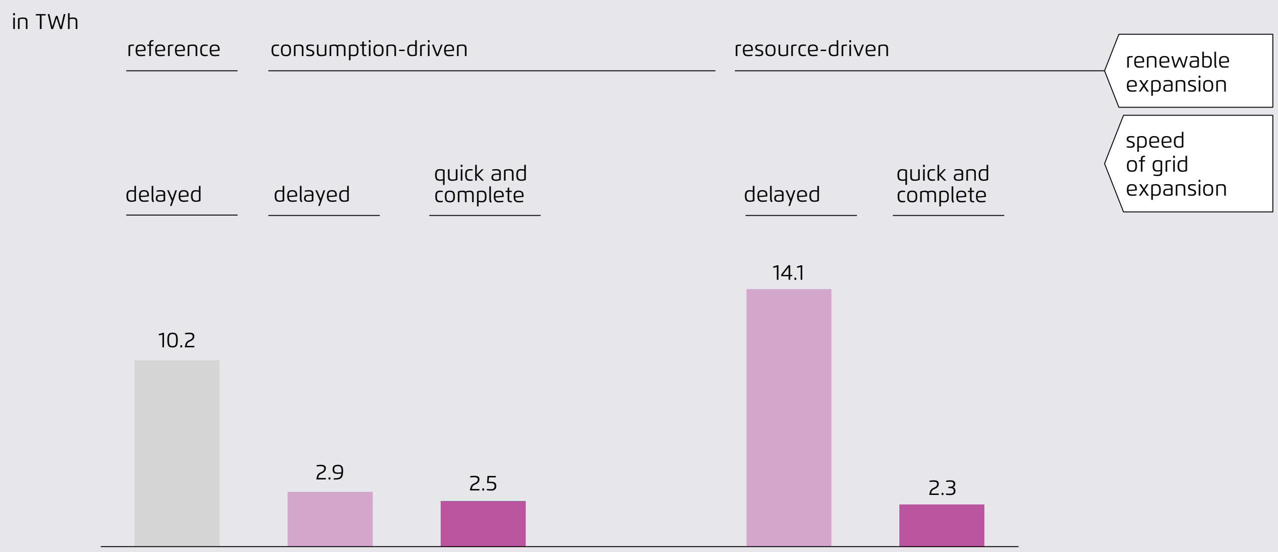
Curtailment in scenarios, 2023

Figure 2.4



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In addition, the scenarios differ in the investment costs for photovoltaics (11 GW more in the consumption-driven scenario) and offshore wind power (2.3 GW more in the resource-driven scenario); however, as the levelized cost of electricity is roughly the same for of photovoltaics and offshore wind, this difference has no relevant effect on direct investment costs.

Savings in residual power generation (including power to compensate for curtailed renewable electricity) in the consumption-driven scenario nearly makes up for the greater investment cost of renewables

In the resource-driven scenario, power from wind turbines in northern Germany largely replaces expensive power from offshore turbines (28 TWh less) and photovoltaics (9 TWh less). But while electricity is then generated much less expensively, the generation profile is less steady (roughly 2,600 to 2,900 full-load hours instead of around 4,100), and this power is mainly produced at the same time as the power that comes from the large number of wind turbines in the north, which are already assumed in the reference scenario. In the case of a delayed grid expansion, roughly 14 TWh of renewable electricity is curtailed, leading to additional costs for the use of conventional power plants that have to generate electricity to replace the lost renewable power. Both the curtailment and the additional cost of generation can be avoided if the grid is expanded quickly and completely. Yet this grid expansion leads to roughly the same yearly cost as the cost for replacing curtailed renewable energy in the scenario considered here.

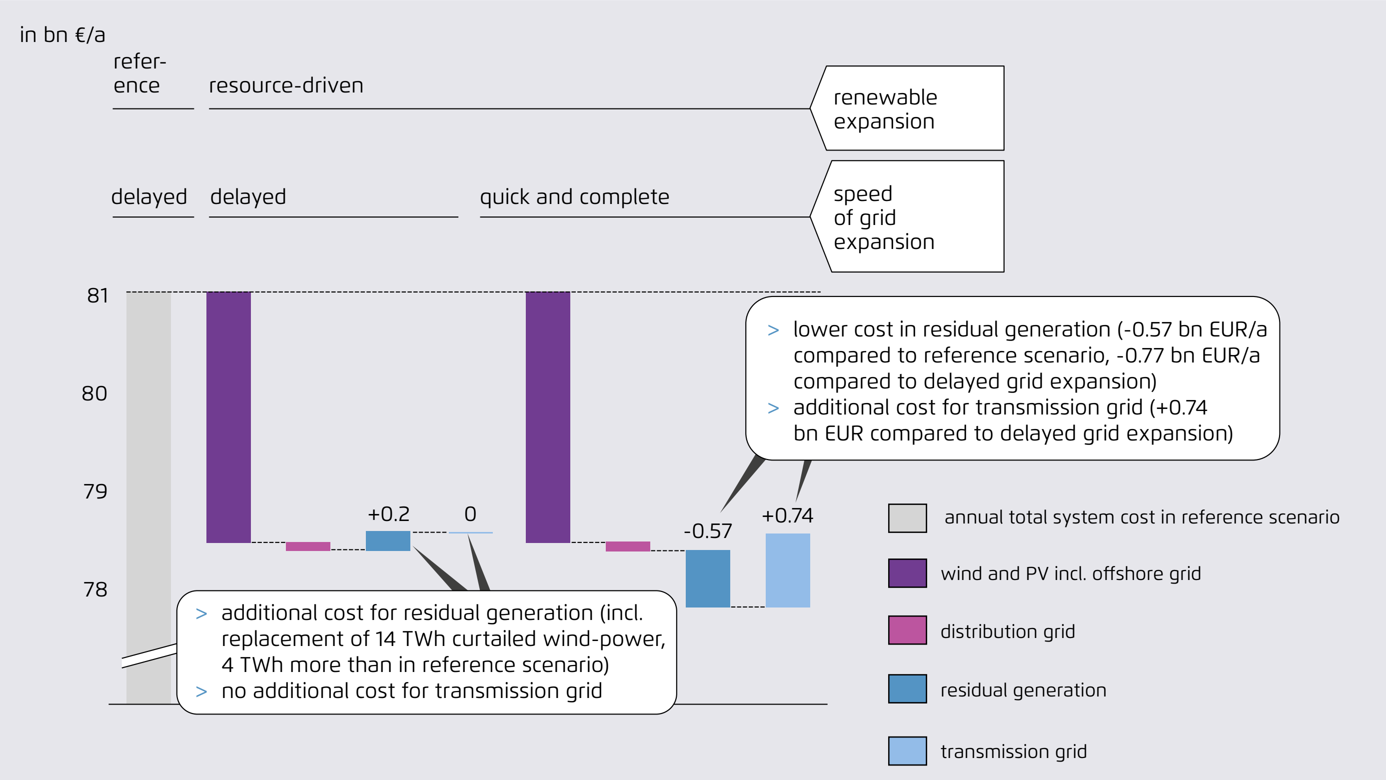
In contrast, in the consumption-driven scenario onshore wind turbines replaced largely by in the interior of Germany, as well as more photovoltaic arrays. Compared to the resource-driven scenario, ten TWh more of solar power and ten TWh less of offshore wind power are generated. Due to the greater geographical distribution of wind turbines across all of Germany and a larger share of photovoltaics, renewable feed-in is more diversified across both time and space than in the other scenarios. This "portfolio effect" leads to a more steady feed-in of the aggregate of all wind turbines and solar arrays, and the cost of residual power supply is reduced. Compared to the reference scenario, this effect leads to cost savings from 0.35-0.6 billion euros a year. Compared to the resource-driven scenario, the cost of residual power supply is approximately 0.5 billion euros a year lower in the consumption-driven scenario, when comparing the two variants with a delayed grid expansion. This difference in cost corresponds to a difference of approximately eleven TWh of curtailed renewable generation a year. The small amount of curtailment in the consumption-driven scenario (two to three TWh) occurs primarily at the distribution grid level.[10]

3. While transmission grid expansion is important in the long run, in a cost-only perspective a few years of delays in expansion are not critical

A closer look at the differences in total cost for power supply in the resource-driven scenario shows the economic effects of a delay in grid expansion versus a quick and complete grid expansion. If upgrades to transmission grids are delayed by around ten years (by 2023, only the "starting grid" in the Grid Development Plan is assumed to be completed in Germany), the grid will not be not able to take up a large amount of renewable power – around 14 TWh – especially from wind turbines in the north. Replacing this curtailed energy with power from conventional power plants leads to additional cost. Depicted in the chart below are the additional costs relative to the reference scenario (in which a delay in grid expansion is assumed as well and already leads to a curtailment of ten TWh). If the grid is expanded quickly and completely, the curtailment of wind power is reduced down to only two TWh, saving costs for replacing curtailed energy and reducing the total cost by 0.8 billion euros a year compared to the case of a delay in grid expansion. However, these savings come at a price; additional costs are incurred by building the grid beyond the starting grid of the Grid Development Plan. In the scenarios analyzed, these costs are

10 The expansion of the distribution grids was assumed to be cost-efficient and not to follow a design that takes on "the last kilowatt-hour": this allows avoiding unnecessary high costs for grid expansion by accepting a small level of curtailment.

Differences in cost of quick vs. delayed grid expansion, 2023 — Figure 2.5



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roughly 0.7 billion euros a year, which is only slightly below the cost of replacing curtailed energy.[11]

The more new wind and solar installations are distributed across Germany, the later significant amounts of curtailment occur, and correspondingly a complete grid expansion is required later

When the renewable expansion is more consumption-driven, a delay in grid expansion even leads to lower overall costs than a quick and complete grid expansion, under the assumptions considered here. A stronger distribution of wind turbines and solar arrays across Germany along with the construction of the "starting grid" of the Grid Development Plan are sufficient to prevent significant amounts of curtailment until 2023. In the consumption-driven scenario, the quick and complete grid expansion allows the remaining power plants to be used more cost-efficiently than in a "delayed-grid scenario", leading to lower generation costs (0.25 billion euros a year less than in the delayed-grid scenario). Yet these savings are lower than the additional cost of grid expansion, which is approximately 0.7 billion euros a year.[12]

11 This comparison of "hard" costs does not include aspects that are difficult to quantify monetarily, such as changes in operational procedures to allow the power supply system to be safely operated with an incomplete grid expansion.

12 It should be emphasized that this study did not determine a cost optimal amount of transmission grid expansion, but rather applied a conventional approach to determine grid expansion as it is commonly used today; a cost optimal amount of transmission grid expansion for the renewable pathway considered here probably lies between the scenario with delayed-grid expansion and fast-and-complete grid expansion.

4. The main findings for 2023 also apply to 2033

With the Grid Development Plan's reference scenario as a starting point, the same logic used for 2023 was also applied to optimized paths for renewables expansion up to 2033

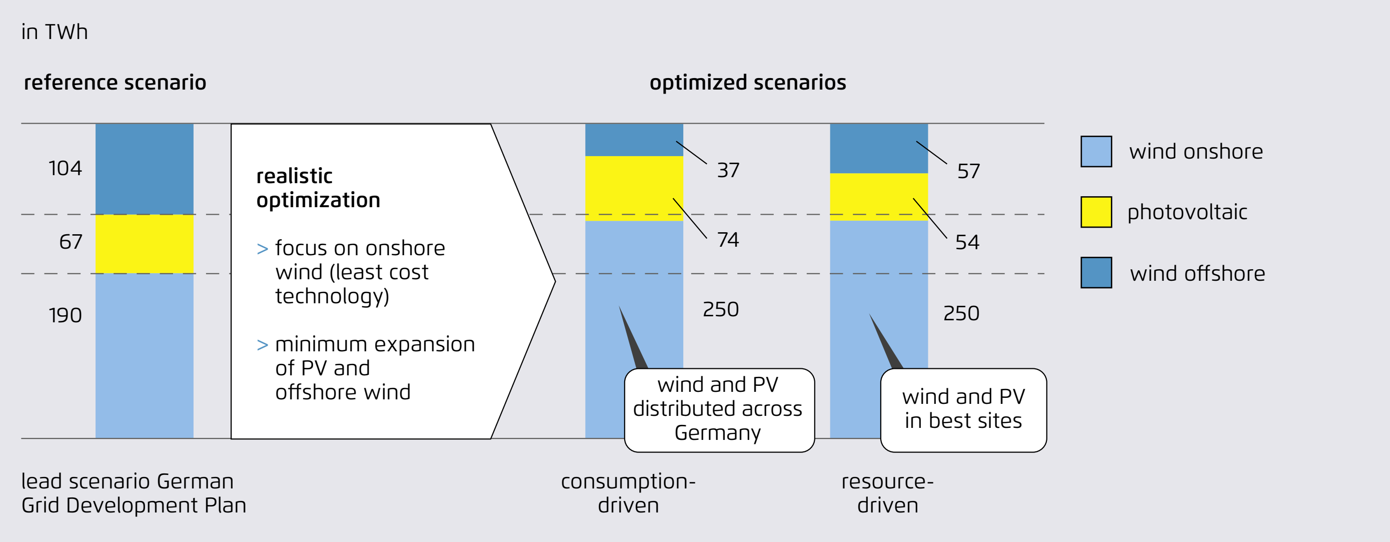
In addition to the year 2023, the study also investigated trends up to 2033. The same logic was applied in designing the scenarios. In accordance with the assumptions for the Grid Development Plan's reference scenario for 2033, however, the amount of wind and solar power is assumed to be greater.

The scenarios with delays in grid expansion assume that the grid expansion projects suggested in the current proposal of the law on grid expansion requirements (*Bundesbedarfsplangesetz*) are delayed by approximately ten years but will be fully implemented by 2033 (they are scheduled to be finished before 2022). Hence these scenarios assume a delayed, yet significant expansion of grids by 2033 – an expansion which the analysis shows to be a crucial adjustment to the new power generation situation. In the scenarios with quick and complete grid expansion, further targeted upgrades are assumed, according to the requirements of the optimized renewable growth paths.

In 2033, the optimized expansion of wind and solar power in Germany could save three to four billion euros a year

The results of the analysis for 2033 are in line with those for 2023 presented above. The growing share of wind and solar power in the power supply (361 TWh in 2033 in all scenarios, compared to 244 TWh in 2023) leads to greater differences in costs. In 2033, the cost savings from optimized growth paths could come in at three to four billion euros a year. Again, the main driver behind these savings is the lower installation costs for renewables (2.8 to 3.7 billion euros a year), in particular the shift from offshore to onshore wind turbines (in the north or distributed in the interior of Germany).

Power generation from wind and solar in the scenarios in 2033 — Figure 2.6



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In 2033, consumption-driven optimization leads to roughly the same savings as resource-driven optimization

Similar to the results for 2023, the two optimization strategies considered lead to similar cost reductions. The savings in the resource-driven scenario – 3.5 to 4 billion euros a year – are somewhat greater than those in the consumption-driven scenario, which range between 2.9 and 3.2 billion euros a year. As in 2023, the main difference between the two growth paths are the investment costs (costs in the consumption-driven scenario are 0.9 billion euros a year higher than in the resource-driven scenario). In return, however, the "portfolio effect" means renewable power is exported to the grid more evenly across time and space, thereby reducing other costs, especially when grid expansion is delayed (the cost of or residual generation in the consumption-driven scenario are 0.6 billion euros a year lower than in the resource-driven scenario). A difference from 2023 appears in the effects on the costs of the distribution grids; in the consumption-driven scenario in 2033, the cost of distribution grids is 0.2 billion euros a year higher than in the resource-driven scenario because installed capacity is greater, which is mainly due to the larger contribution of photovoltaic power.

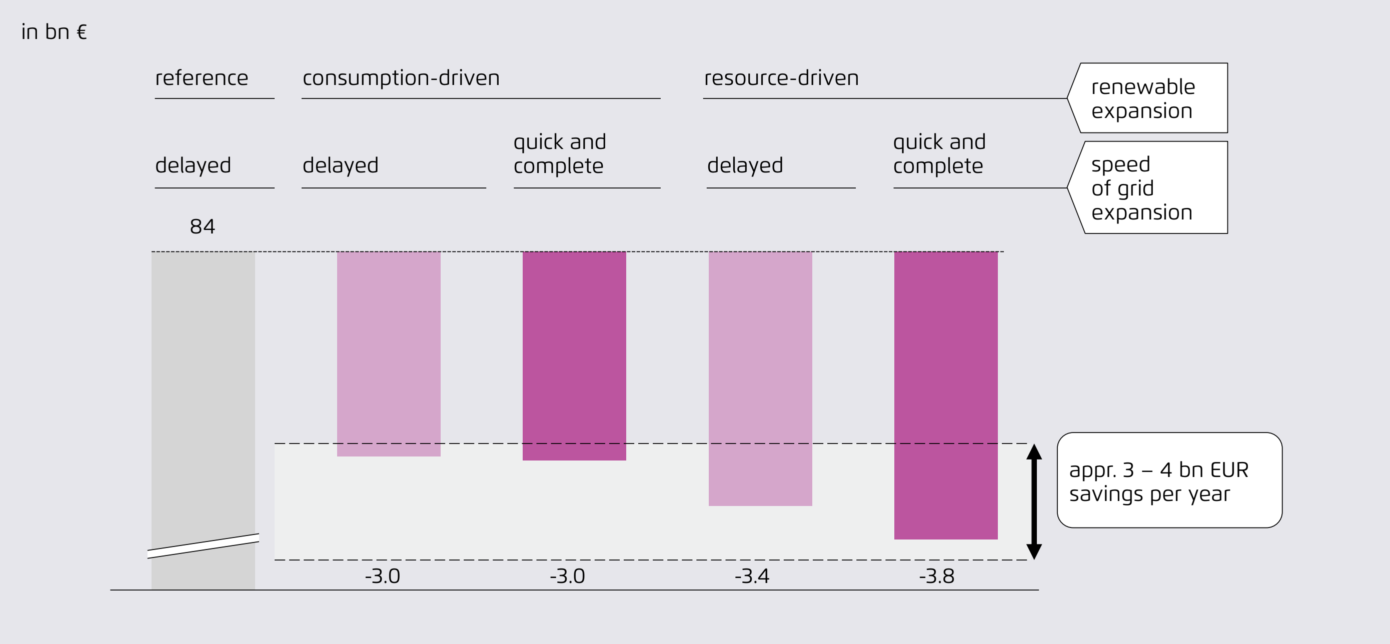
In all scenarios, grid expansion leads to lower total system costs in 2033

The greater share of wind and solar power in 2033 increases effects on the residual power supply system in Germany, and the amount of power that the grid cannot take up increases in all scenarios. Expanding transmission grids beyond the level of expansion assumed in the delayed scenario for 2033 (based on the current draft of the *Bundesbedarfsplangesetz*) considerably reduces the amount of curtailment. In the consumption-driven scenario, additional grid expansion reduces curtailment from 35 to 25 TWh. In the resource-driven scenario, grid expansion reduces curtailment from 47 to 27 TWh. In total, additional grid expansion saves 0.2 to 0.5 billion euros a year in 2033.

5. From today's perspective, the PV + battery breakthrough scenario is not a cost-efficient alternative

A sensitivity analysis was conducted on the PV + battery breakthrough scenario, in which it was assumed that there would be a massive rollout of photovoltaics in combination with battery storage by 2033 (150 GW a photovoltaics with 40 GW of battery storage). In return, the scenario has some

Total annual cost of power supply and savings compared to reference scenario in 2033 — Figure 2.7



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20 gigawatts of wind turbines less than the basic scenario does for 2033 so that, in total, the amount of electricity from renewables remains the same. The simulation revealed that a power supply system with 150 GW of photovoltaics and 40 GW of distributed storage is possible in technical terms and would not pose any fundamental risk for the reliability of power supply in Germany.

The question was therefore how much the cost of a typical solar array with battery storage would have to drop for such a scenario to lead to similar overall system costs.

The savings from residual power generation are considerable, yet a similar amount of grid expansion is required

To find out what a system would have to cost, we first took a look at the indirect cost effects of such an expansion path. Here, the dominant effect is on the cost of residual power generation. By 2033, the savings will have reached 1.5 billion euros per year, far more than the savings in the other scenarios. On the one hand, most of the renewable energy in this scenario is generated during the day, when there is the most demand; as a result, power plants with the greatest marginal cost are offset. On the other, the large storage capacity means that less renewable power is lost – and hence that less power has to come from conventional power plants. In return, the cost savings from fuel consumption are considerable. And while the transmission grid also would not need to be expanded as much, the savings only make up around one percent of those for residual power generation at around 35 million euros per year.

The cost of a typical PV + battery system would have to drop by more than 80 percent below the current level for such a growth path to lead to similar overall system costs

For this expansion path focusing on PV + battery systems to lead to the same costs overall as the optimized growth paths,[13] the cost of a typical homeowner system (four kilo-

13 For a comparison, the average of the costs of the four scenarios investigated was used here

Required cost reduction for a typical photovoltaic + battery system until 2033 — Figure 2.8

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watts of photovoltaics plus a battery with a connection capacity of two kilowatts and a storage capacity of six kilowatt-hours) would have to drop to around 2,000 euros.[14] The cost of such a system is currently, however, several times greater – under the assumptions made here, it is around 11,000 euros at the end of 2013.[15] Costs would therefore have to be reduced by around 80 percent for such a scenario to lead to similar costs as the optimized scenarios would by 2033.

The findings support the robustness of the optimized growth paths investigated. Both wind power and grids are needed in any case

From today's perspective, it seems very unlikely that the cost of a PV + battery system can be reduced by 80 percent, though that outcome cannot be ruled out. If we assume that such a breakthrough in costs can be reached and therefore massively expand PV growth towards 150 GW of installed capacity and 40 GW of battery storage, we run the risk of considerably increasing the overall cost of power generation in Germany.

The investigation also shows that even this scenario would require the transmission grid to be considerably expanded and that a lot of wind turbines would need to be installed to make up for the lower PV power production during the winter. The sensitivity analysis therefore supports the robustness of the findings for both optimized growth paths.

14 This also implies an additional reduction in the cost of PV panels to a similar extent. The assessment of the required cost-reduction path evaluates all PV growth – including systems without battery storage – with this cost reduction.

15 Under the assumptions used here, around 53 percent of the cost of such a system in 2013 is devoted to the battery. Current prices for battery systems (April 2013) are much higher than the costs assumed here.

3. Conclusions

The findings of the comparison of total system costs for renewable expansion paths with different regional focuses lead to the following conclusions:

1. Policy makers have a large scope of action in designing policies for the regional distribution of onshore wind and photovoltaics

The cost differences between different regional expansion paths for onshore wind and photovoltaics are very small (around 0.1 billion euros a year in 2023), so that neither the resource-driven path nor the consumption-driven path can scientifically be considered to offer cost benefits. Both growth paths lead to annual savings of around two billion euros relative to the reference scenario based on the assumptions in the German Grid Development Plan. These savings mainly result from the slower expansion of offshore wind in favor of faster expansion of onshore wind.

2. To achieve a cost-effective renewables expansion and enable technology development at the same time, offshore wind power should continue to be developed, though at a slower pace than current government targets foresee

Costs can be reduced considerably (by around two billion euros a year in 2023) if the focus of expanding wind power shifts from offshore to onshore wind (in the north or the south). At the same time, there is still considerable potential to be tapped in terms of technological innovations and cost reductions for offshore wind. This progress is not possible without further expansion. The challenge here lies in finding the right balance.

3. Grid expansion is an important prerequisite for the *Energiewende*. The "starting grid" in the *Bundesbedarfsplan*[16] is urgently needed. In a cost-only perspective, a few years of delays for the additional transmission lines foreseen in the *Bundesbedarfsplan* would not be critical

Expansion of renewables does not have to wait until the complete grid expansion foreseen in the *Bundesbedarfsplan* (beyond the "starting grid") is implemented. While delays in grid expansion lead to an increase in curtailment, the cost incurred by this curtailment would be roughly equivalent to the avoided cost for grid expansion up to 2023 in the scenarios considered. Optimization of total cost of power supply must be considered much stronger in future grid planning.

The outlook for 2033 shows that a quick and complete grid expansion saves up to 0.5 billion euros a year in the long term. Moreover, it should be noted that even in the scenario with delayed grid expansion, considerable grid expansion is assumed to be achieved until 2023, consisting of 24 measures in "starting grids." In summary, the *Energiewende* needs the grid to be expanded – the question is not whether, but when.

4. A power supply system with a large share of distributed PV + battery storage systems (150 GW of PV and 40 GW of storage) would be technically possible but only make economic sense if costs drop by 80 percent by 2033. From today's perspective, such a cost reduction is very unlikely, though not impossible

16 The *Bundesbedarfsplan* is a current proposal for a law which defines the need for grid expansion in Germany in the next years. The so-called starting grid includes those grid upgrades already included in the grid expansion law of 2009 (*EnLag*)

If we assume that such a breakthrough in costs can be reached and therefore massively expand PV growth towards 150 GW of installed capacity and 40 GW of battery storage, we run the risk of considerably increasing the overall cost of power generation in Germany.

The need for roughly the same grid expansion even in this scenario and the need for a large amount of wind power in the winter suggest that, from today's perspective, the other optimized growth paths should be pursued. Expansion planning should be designed so that it can be adapted flexibly to technological breakthroughs in the next few decades.

Annex I: Methods and Assumptions

Analysis of total system cost of the power supply by Consentec

In this study, the total system cost of the power supply was considered and modeled in detail by Consentec: the cost of power generation by wind turbines and solar arrays (mostly investment costs), the cost of residual power supply (other renewables and remaining fossil power plants in Germany and Europe), and the cost of expanding transmission and distribution grids.

The cost of expanding the transmission grids was determined in detail according to the specific requirements for each scenario of renewable expansion, or in the scenarios with an assumed delay in grid expansion, based on the underlying assumptions. The cost of expanding the distribution grids was assessed using a simplified model of distribution grids in Germany and according to the renewable expansion paths. The cost of the residual power supply in Germany and Europe was determined in a detailed model of the entire European power market, power plant by power plant, with a resolution down to the hour.

High-resolution data for wind and solar power on the grid in Germany from Fraunhofer IWES

Fraunhofer IWES provided high-resolution data across space and time for wind and solar power on the grid. Based on actual historic weather data from the German Weather Service for 2011 (based in turn on re-analysis data from the COSMO EU model, including wind measurements from more than 200 stations in Germany) and assumptions about future technical designs of wind turbines and solar arrays in 2023 and 2033, feed-in time series were calculated. For the different renewable expansion paths, the installed capacity for each technology was broken down to the roughly 360 grid nodes in Germany based on each scenario's distribution logic; then the renewable power fed to the grid at each node was calculated for each hour (8.760 hours a year). In line with recent developments in Germany, different types of wind turbines were assumed to be built in locations with high wind speeds as opposed to those built in locations with low wind speeds (less than 8.5 m/s average wind speed at hub height). Additional costs for such different wind turbine designs were considered.

All assumptions are based on the German Grid Development Plan

The starting point of the analysis and of all key parameters were the assumptions of the German regulator laid out in the scenario framework for the 2013 Grid Development Plan and, if not mentioned there, the assumptions published by the German transmission grid operators in the 2012 Grid Development Plan. Where no assumptions were available or where the plausibility of these assumptions seemed doubtful, Consentec and Agora jointly developed realistic assumptions (such as concerning the expansion of renewables in Europe). All relevant assumptions will be published in detail in the final report.

Investment costs for wind and solar power based on the lead study of the German ministry of environment

The costs of new installations of onshore wind power, offshore wind power, and photovoltaics up to 2013 are based on the assumptions in the German Ministry of the Environment's lead study on renewable energy (*Leitstudie*, 2012). Based on a comparison of these assumptions with current market prices, the assumed future cost reduction per technology was adapted to be anticipated (five years faster for photovoltaics) or delayed (three years later for offshore wind power). The additional cost of wind turbines for locations with low wind speeds relative to wind turbines for locations with stronger winds and the additional cost of photovoltaic rooftop systems relative to ground-mounted systems were taken into account.

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Studie von Energy Brainpool

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How can we make the energy transition succeed? What specific laws and targets are needed, and what steps need to be taken? Agora Energiewende aims to pave the way for Germany to take the right path in the coming years. We see ourselves as a think tank and political lab, promoting dialogue among those who shape energy policy.

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