Cost optimal expansion of renewables in Germany

SUMMARY OF THE INTERIM RESULTS OF A STUDY CONDUCTED BY CONSENTEC GMBH IN COOPERATION WITH FRAUNHOFER IWES

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Agora Energiewende

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Fraunhofer IWES

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IMPRINT

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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

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Contents

I. Question and approach of the study

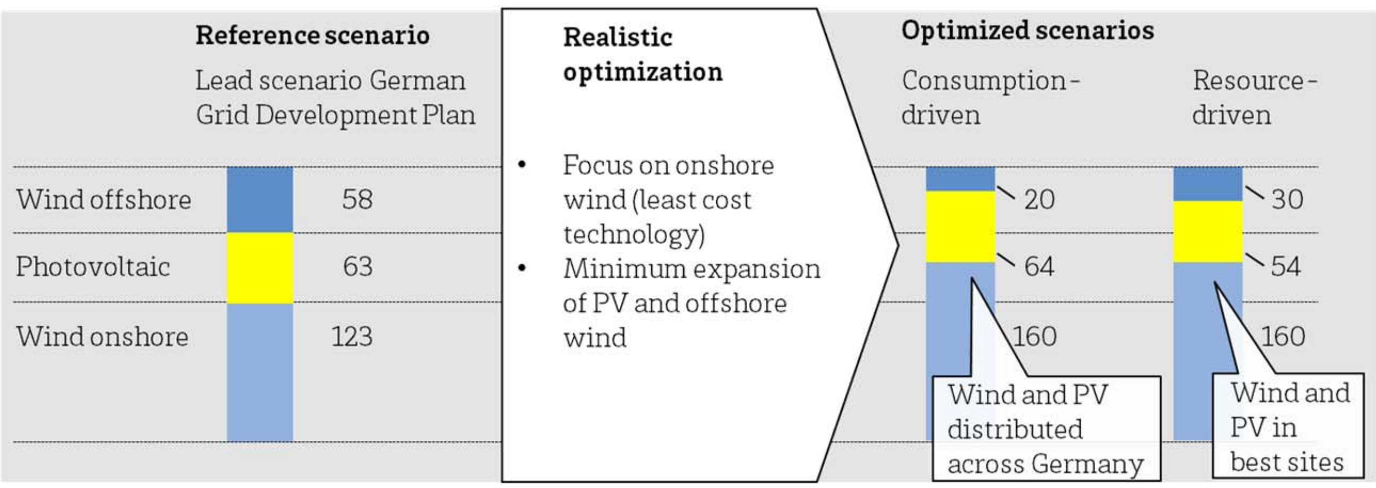
Should wind turbines and solar arrays be primarily built in locations with the best wind and solar conditions or close to where power is consumed?

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 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.

Power generation from wind and solar in the scenarios in TWh, 2023



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 are 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 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.

[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.

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 on 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]

A glance at the "PV breakthrough" scenario

In addition to the interim results presented here, an additional scenario is currently being investigated that analyses the effects of a breakthrough in photovoltaics and battery storage systems leading to a tremendous growth up to 150 GW in 2033. The focus of this analysis is not on the total cost of power supply, which would be pure speculation in such a breakthrough scenario anyway. Rather, we want to see to what level the cost must be reduced in order for such a scenario to reach the same range as the other scenarios. In addition, this scenario will test the robustness of the findings of the other scenarios. The results will be published together with the final report (April 2013).

[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*)) 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.

II. Results

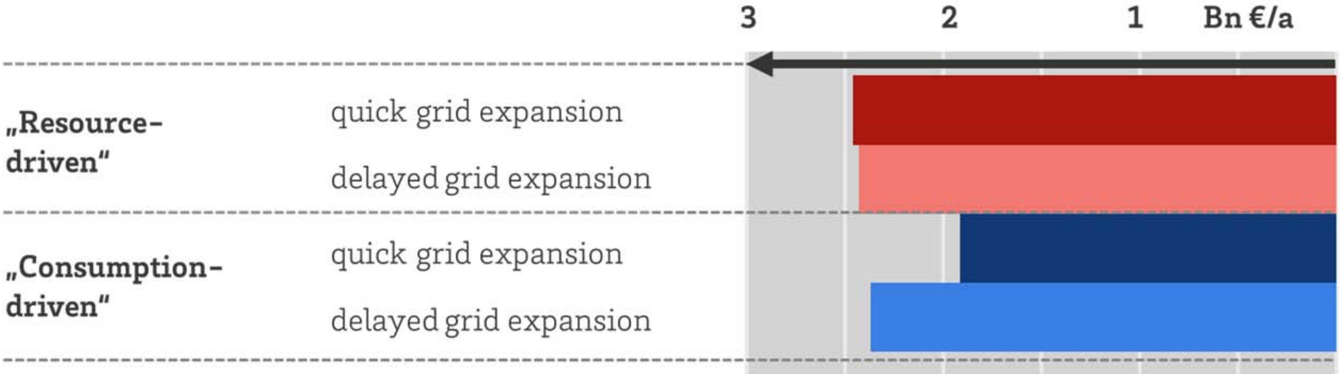
1. In 2023, an optimized expansion of wind and solar power in Germany could save around two billion euros a year

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] This includes 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 (less full-load hours), more wind turbines are needed onshore than offshore. Yet due to the great difference in investment costs (per GW) the total investment costs are significantly lower in the end.[7] This large difference in total investment cost between wind offshore and wind onshore is by far 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).

Cost savings compared to the reference scenario, 2023

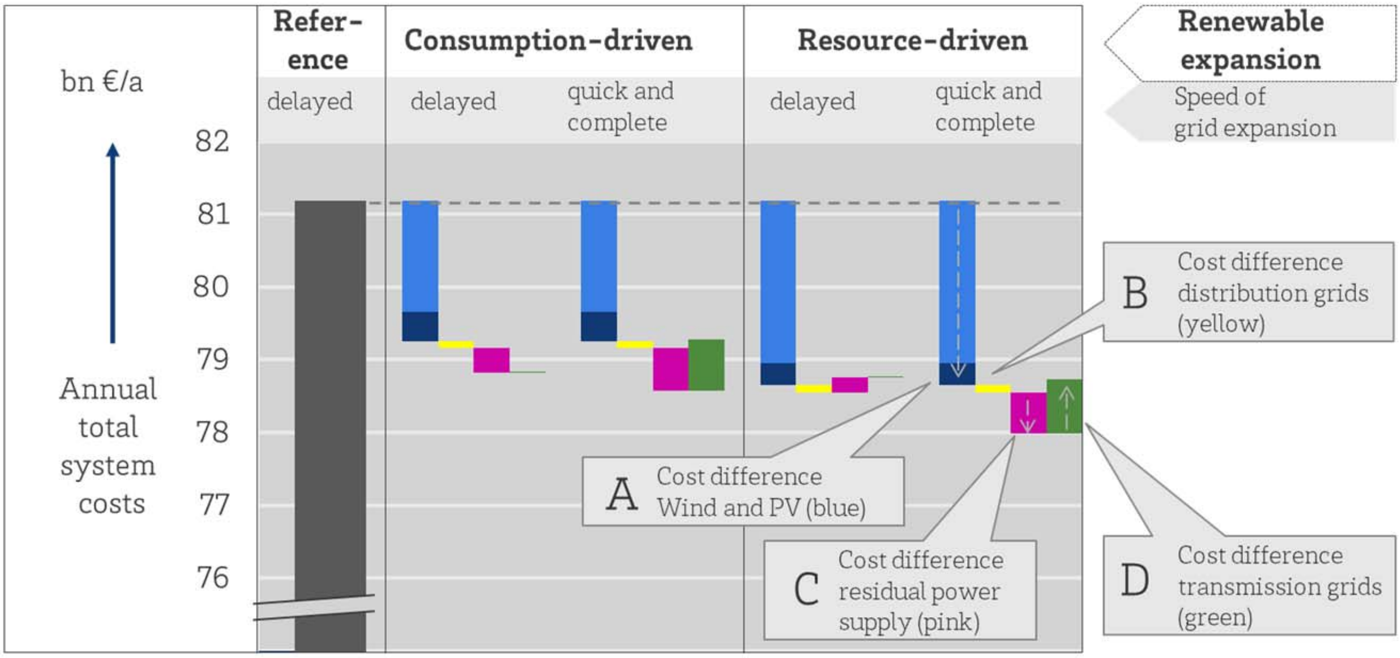


5 The reference scenario includes the growth path of renewables in the lead scenario of the German Grid Development Plan and the assumption of a ten year delay in grid expansion.

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.

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.

Differences in cost of scenarios compared to reference scenario



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. The three principal indirect effects were studied in detail:

- Different cost for 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.
- Different cost for 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.

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

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

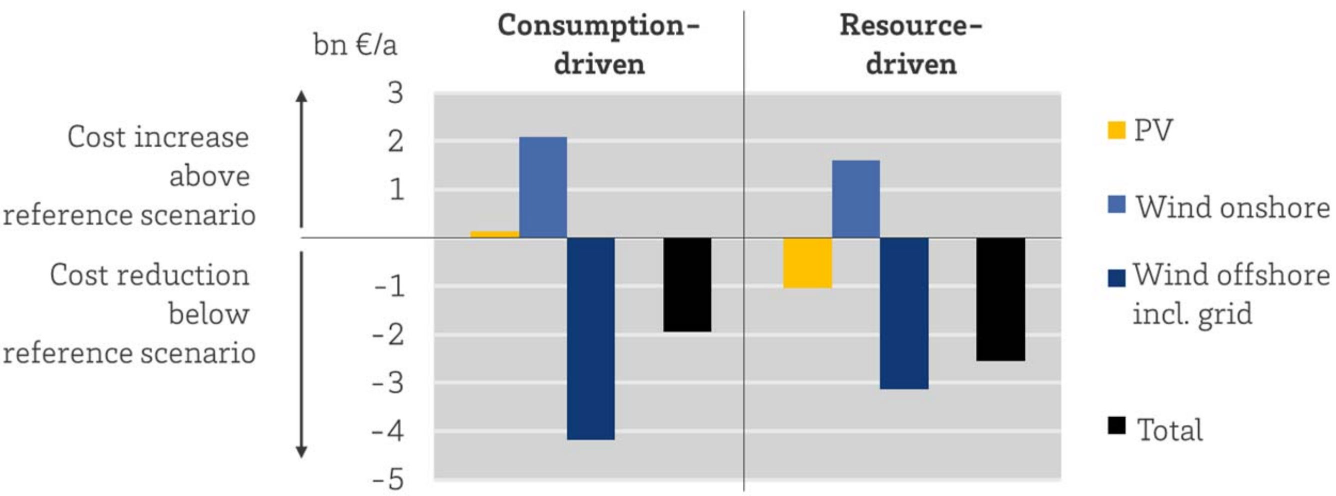
The two optimization strategies analyzed lead roughly to the same cost reductions relative to the reference scenario. When optimization focuses on a resource-driven expansion, around 0.1 billion euros more a year can be saved than when the focus is on consumption-driven expansion. This surprising finding is the result of two opposite effects that roughly compensate for each other in the scenarios. In the resource-driven scenario, investment cost 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).

The larger savings in the resource-driven scenario are mainly driven by the lower investment costs for onshore wind power. According to 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, and 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). 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 levelized cost of electricity of photovoltaics and offshore wind is roughly the same, this has no relevant effect on direct investment costs.

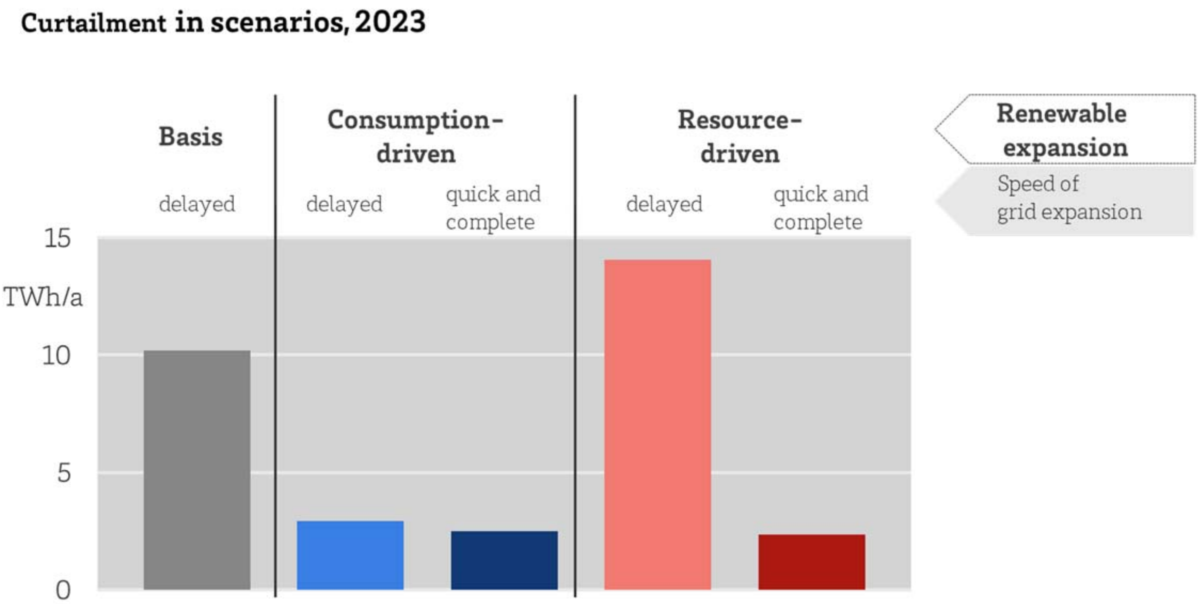
Savings in residual power generation (including power to compensate for curtailed renewable electricity) in the consumption-driven scenario nearly makes up for the greater investment cost of renewables

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 cheaper, 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 cost for the use of conventional power plants that have to generate

Differences in investment cost of wind and PV plants, 2023



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



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 offshore wind is replaced largely by onshore wind turbines 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 corresponding to a difference of approximately eleven TWh curtailed renewable generation a year. The small amount of curtailment appearing in the consumption-driven scenario (two to three TWh) occurs primarily at distribution grid level.[10]

[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.

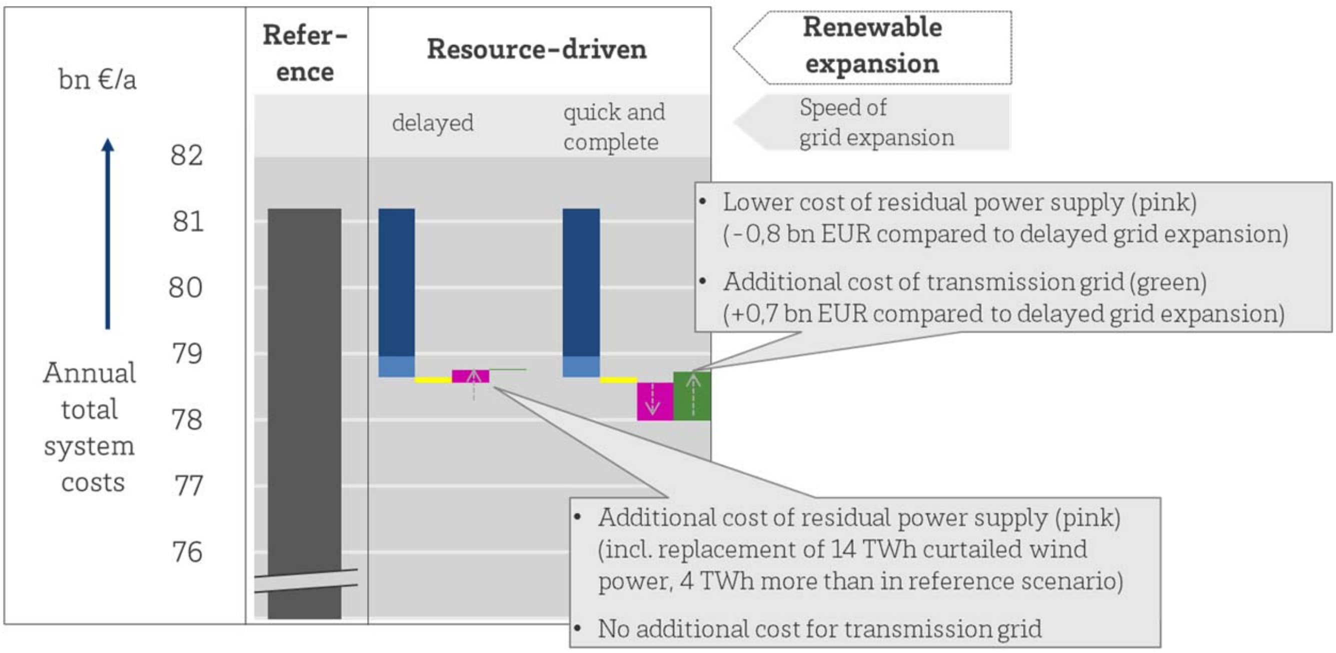
3. While transmission grid expansion is important in the long run, in a cost-only perspective a few years of delays in expansion are not critical

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 is 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 in comparison with 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. This saves costs for replacing curtailed energy and reduces 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 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-

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



[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.

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]

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

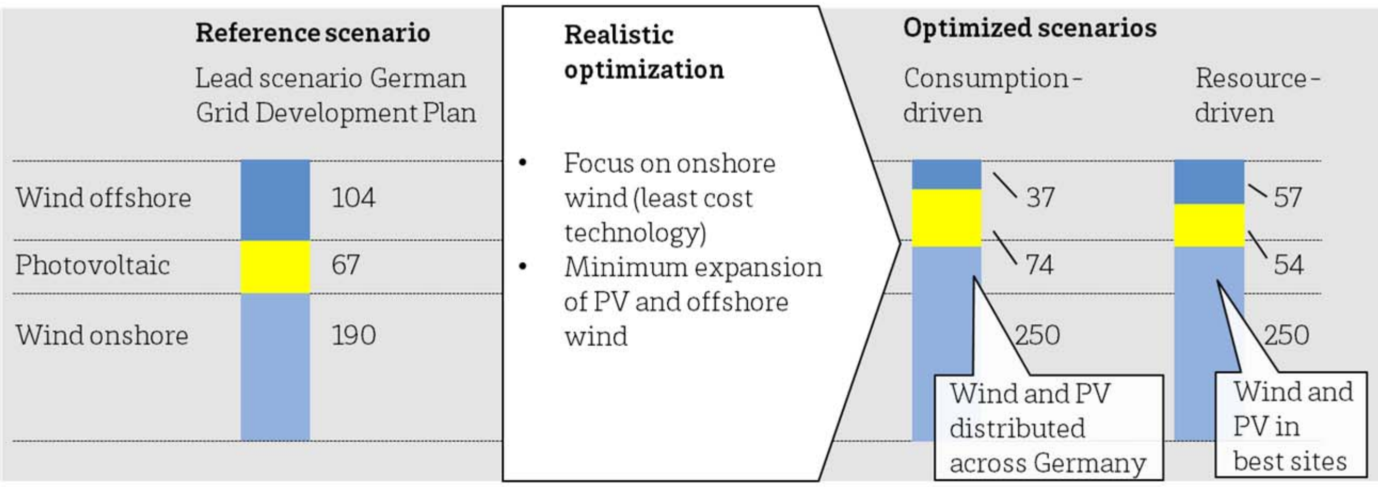
In addition to the year 2023, the study also investigated trends up to 2033. The same logic was applied in designing the scenarios. In accordance with the assumptions for the Grid Development Plan's reference scenario for 2033, however, the amount of wind and solar power is assumed to be greater.

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 (*Bundesbedarfs-plangesetz*) 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 TWh, 2033



[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.

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 (cost 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" of the feed-in of renewables which is more evenly spread across time and space, reduces other costs, especially when grid expansion is delayed (costs for 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.

III. 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*[13] 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, a considerable grid expansion is assumed to be achieved until 2023, consisting of 24 measures of the so-called starting grids. In summary: the *Energiewende* needs the grid to be expanded – the question is not whether, but when.

[13] 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")

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: cost of power generation by wind turbines and solar arrays (mostly investment costs), cost of residual power supply (other renewables and remaining fossil power plants in Germany and Europe), as well as 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 feed-in from wind and solar power in Germany from Fraunhofer IWES

Fraunhofer IWES provided high-resolution data across space and time for wind and solar feed-in. 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 feed-in 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 *lead study renewable energies* of the German Ministry of the Environment (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, as well as additional cost for photovoltaic rooftop systems relative to ground-mounted systems was taken into account.

Annex II: Detailed results by Consentec

Assessing optimization strategies for the expansion of renewables in Germany

Discussion of results

Berlin | 01.03.2013 |

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Tasks

Main question

> How do the various strategies/variants for the expansion of renewables in Germany affect the cost of power supply?

- Dimensions of various renewables expansion strategies
  - Technology mix (onshore versus offshore wind versus PV)
  - Large-scale geographical distribution / regional distribution (e.g. wind in the north vs. versus wind in the south)
  - Small-scale geographical distribution / local distribution (e.g. more PV rooftop instead of ground-mounted PV)
  - Explicitly not part of the expansion strategy: total renewable generation in TWh
  - Speed with which grid is expanded is a considerable uncertainty → possible effects should be taken into account
- Costs that are influenced by renewable expansion strategy
  - Variable cost of conventional generation because of differences in dispatch
  - Investment cost for additional renewable generation because of different installed capacities
  - Cost of transmission grid expansion or cost of renewable curtailment in case of delays in grid expansion
  - Cost of distribution grid expansion

> The objective is to compare cost for various expansion scenarios as a reference for recommendations for a future, optimized renewables growth path

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Scenario definition

Design and implementation of scenarios

Dimensions of scenarios investigated (1/2)

Reference scenario

Different speed of transmission grid expansion

Same as scenario framework of German Grid Development Plan 2013

Differences in expansion of renewables
- Focus on onshore wind (least cost technology)
- Minimum expansion of PV and offshore wind

Consumption-driven renewables expansion
- More onshore wind spread across all of Germany
- A bit more PV spread across all of Germany
- A lot less offshore wind
- Local optimizations of distribution grids

Resource-driven renewables expansion
- More onshore wind in the north
- Les PV in the north, target of 52 GW is ceiling
- Less offshore wind
- No local optimization of distribution grids

All analysis done for 2023 and 2033, with different shares of renewable generation

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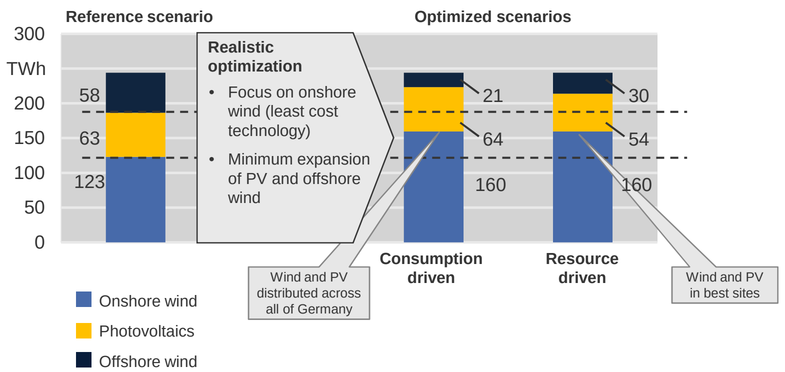
Definition of scenarios

Design and implementation of scenarios

Power generation per technology in renewable expansion paths (2023)



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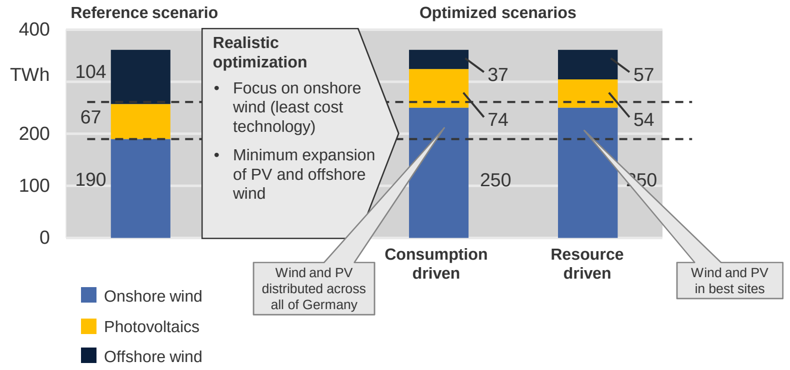
Definition of scenarios

Design and implementation of scenarios

Power generation per technology in renewable expansion paths (2033)



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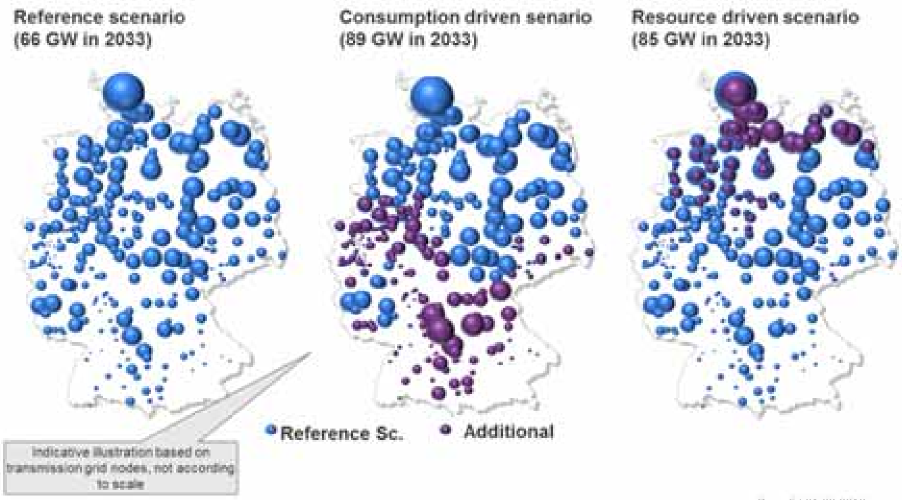
Definition of scenarios

Design and implementation of scenarios

Distribution of wind onshore in different scenarios (2033)



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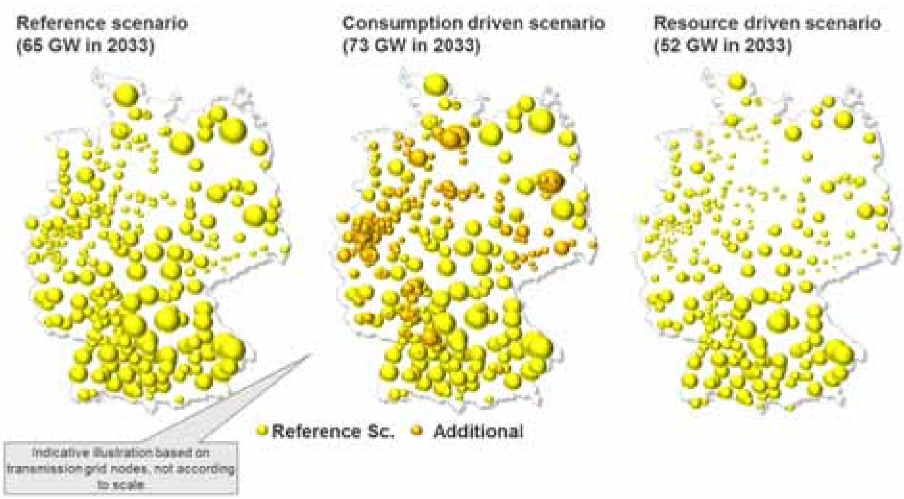
Definition of scenarios

Design and implementation of scenarios

Distribution of PV in different scenarios (2033)



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Definition of scenarios

Design and implementation of scenarios

Dimensions of scenarios investigated (2/2)

Grid expansion assumed to be delayed in the reference scenario

Reference scenario

Different speed of transmission grid expansion

Differences in expansion of renewables

Delayed grid expansion:

Expansion of transmission grid is delayed:

- In 2023, the “starting grid” of the grid development plan 2012 (largely EnLAG) is complete
- In 2033, current proposals for the grid expansion law of 2013 (Bundesbedarfsplan-gesetz) are implemented

Quick-and-complete grid expansion:

Transmission grids are completely upgraded without delays, in accordance to the specific requirements of the renewables growth path

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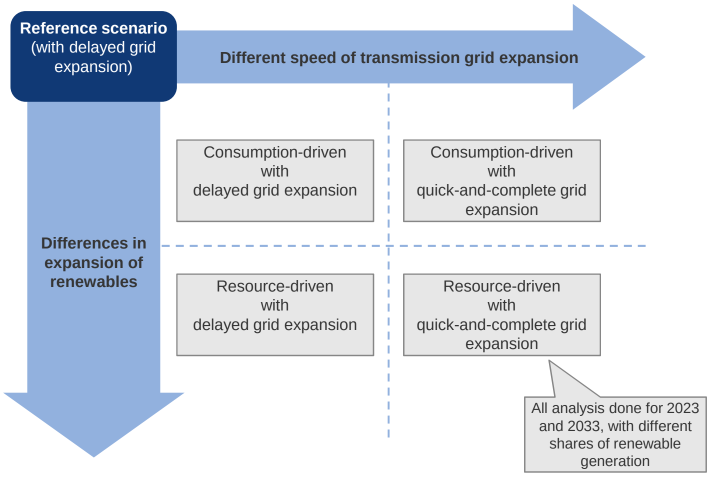
Definition of scenarios

Design and implementation of scenarios

Dimensions of scenarios investigated (2/2)



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Definition of scenarios

Basic assumption for all scenarios

Conventional power plants

> Installed capacities per primary energy source in conventional power plants is based on assumptions in grid development plan
  - » This applies to all parameters , incl. fuel prices, etc.

> Use of power plants is result of calculations and depends on scenario definition (influence of renewables growth on residual load)
  - » Installed capacity of conventional power plants are equal across all scenarios

European grid expansion

> As in the grid development plan, assumptions for European grid expansion are used based on the TYNDP of ENTSO-E

> Assumptions on German import and export capacities are greater in the scenarios with quick-and-complete grid expansion than in the delayed case (including related assumptions on grid expansion in neighboring countries)

European renewables growth

> As in the German grid development plan, the assumptions from ENTSO-E on renewables expansion in Europe are applied (partially adjusted)

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Methodological procedure

Overview

Scenario definition, simulation calculations, and assessment of results

Definition of scenarios

German grid expansion is input or output depending on scenario

- Conventional power plants
- European and German grid expansion
- German RES growth: Tech mix | geogr. regional | geogr. local

Calculations

only relevant if German grid expansion is not an input

- European market simulation (dispatch)
- German transmission grid: Load flow simulation | Expansion simulation
- Distribution grid analysis (simpl. grid model)

Assessment of results

- Variable cost of power generation
- Cost of curtailment
- Expansion costs transmission grid
- Expansion costs distribution grids

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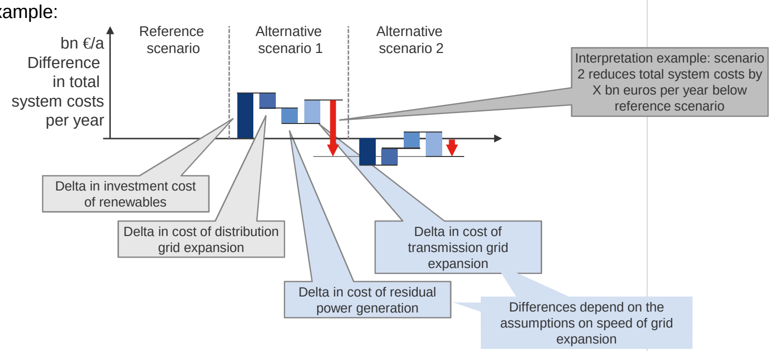
Methodological procedure

Assessment of results

Comparison of total cost of power supply in all scenarios

> Incremental comparison of costs influenced by the scenarios

> Example:



Additional assessment parameter

> Extent to which must-run generation (esp. renewables) is curtailed in Germany

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Results 2023

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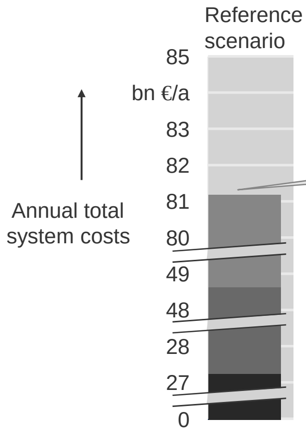
Cost comparison scenarios 2023

Starting point: annual total system costs in reference scenario



Estimate of overall total system costs based on assessment of annuity cost of all existing power supply infrastructure in Germany (power plants, grids, renewables generators) based on new investment cost plus variable and fixed operating costs

In detail, total system costs include:

- Annuity investment costs for renewable capacities (existing plus newly installed capacities in reference scenario) plus variable power generation costs (biomass)
- Annuity investment costs for existing transmission and distribution grids (mainly lines and transformers), including assumed expansion (transmission grid assumed to be starting grid of German Grid Development Plan) and required expansions (distribution grids) in the reference scenario
- Annuity investment costs of conventional power plants plus variable power generation costs, including cogeneration (fuel costs and cost of carbon dioxide certificates)

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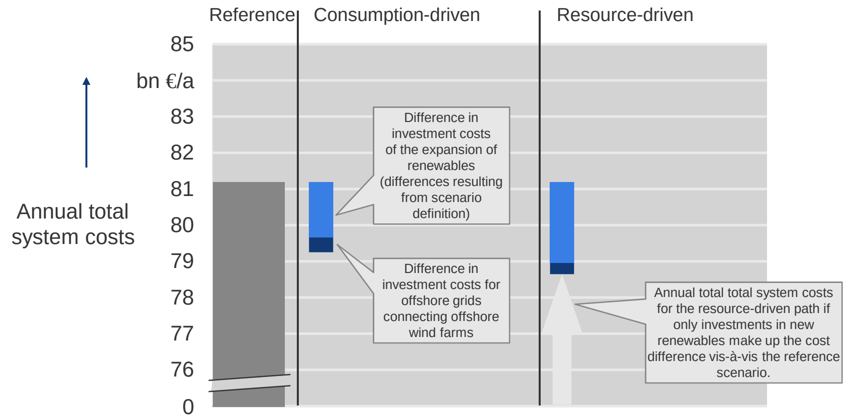
Cost comparison scenarios 2023

Cost differences for renewables growth



> Both alternative growth paths have lower costs for the expansion of renewables (while total renewable generation is equal)

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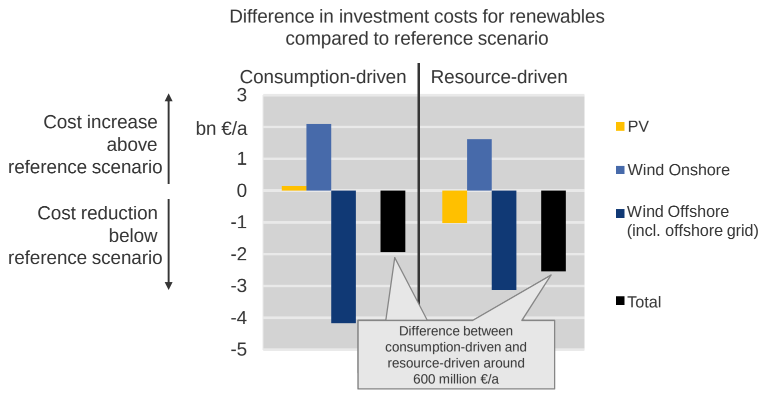
Cost comparison scenarios 2023

Detailed view on direct cost of renewables



> Both optimized paths have lower renewable investment costs by around 2 to 2.5 billion euros per year, with same amount of renewable generation
- » Cost reductions in both scenarios mainly because of lower offshore wind expansion compared to the reference scenario

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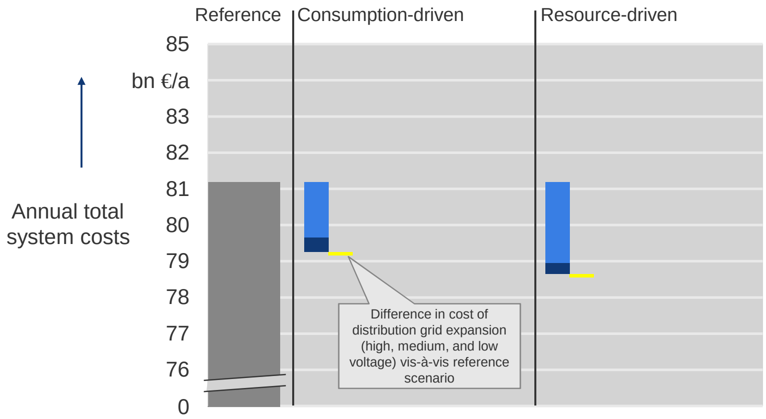
Cost comparison scenarios 2023

Cost differences for distribution grid expansion



> Both optimized paths have lower costs for distribution grid expansion at around 90-95 million €/a

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Cost comparison scenarios 2023

Detailed assessment of distribution grid expansion

- Comparison of reference scenario and resource-driven expansion
  - Despite practically the same amount of renewable generation capacity in distribution grids (PV and onshore wind), costs are lower in the resource-driven scenario than in the reference scenario
  - Overall cost effect is result of two opposite effects
    - Larger capacity of onshore wind increases cost at high-voltage level in resource-driven scenario
    - Lower capacity of PV leads to lower cost, especially at low-voltage level and sometimes medium voltage level
    - Overall, the latter effect outweighs the former

- Comparison of alternative growth paths
  - Cost for expansion of distribution grid are nearly identical
    - higher costs at low-voltage level in the consumption-driven scenario because of higher installed capacity in PV (some 10 GW more than in the resource-driven scenario)
    - lower cost at medium and high-voltage level in consumption-driven scenario despite higher installed capacity for onshore wind (→ effect of distributed onshore wind power)
  - Generation closer to consumption reduces specific cost of distribution grids (cost per MW of installed renewable capacity)
  - This effect is offset by greater total renewable capacity installed (in MW)

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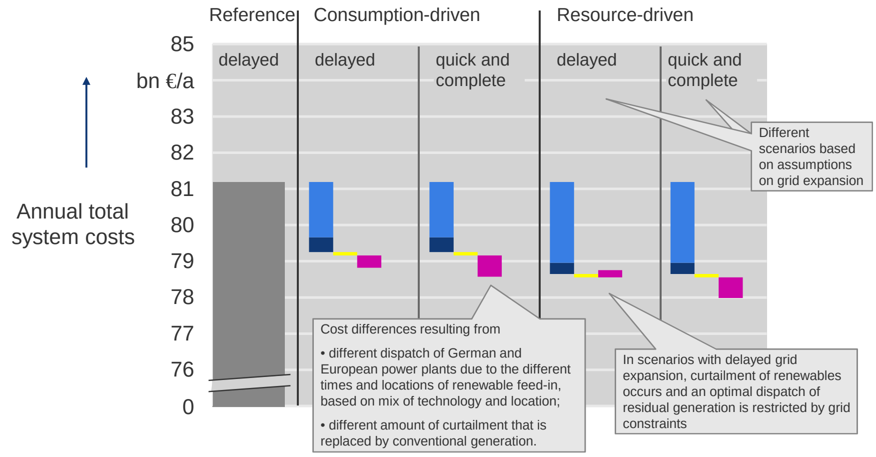
Cost comparison scenarios 2023

Cost differences in residual generation



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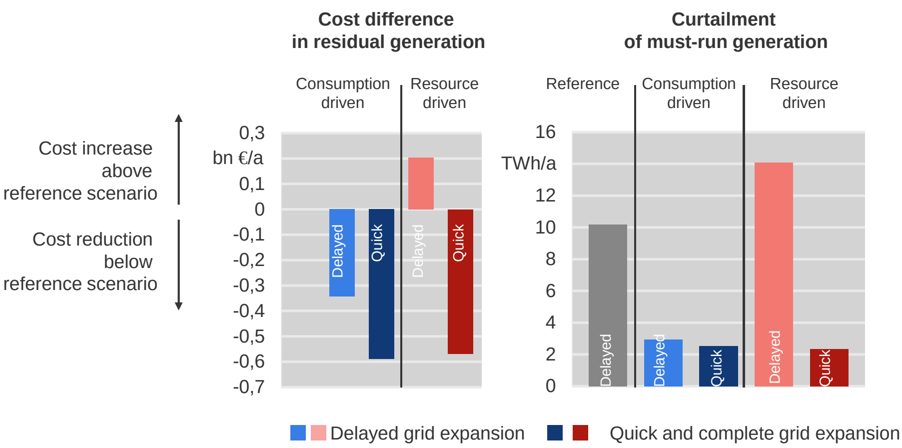
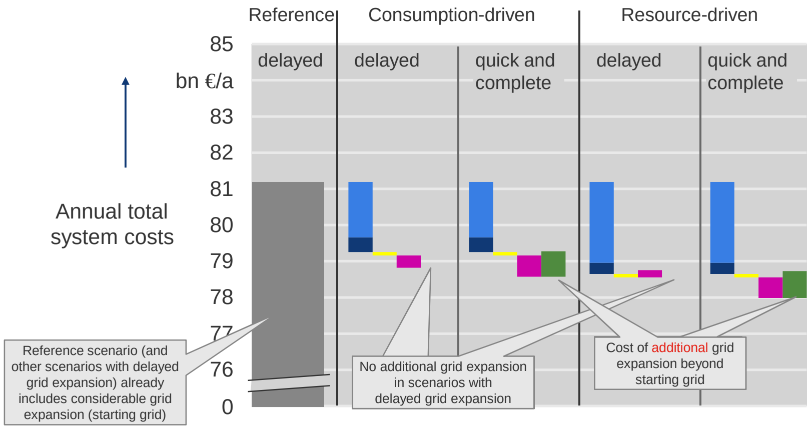
Cost comparison scenarios 2023

Detailed view of residual generation costs and curtailment



Cost comparison scenarios 2023

Cost differences: transmission grid expansion



Cost comparison scenarios 2023

Detailed view on of transmission grid expansion

> Compared to today, the starting grid already constitutes considerable grid expansion, even in the scenarios assuming a delayed grid expansion

> Additional need for grid expansion in scenarios with quick-and-complete grid expansion to a varying extent

» The consumption-driven scenario requires fewer grid expansion in the north than the resource-driven scenario does, but more grid expansion in the southwest

» The resource-driven scenario requires grid expansion especially on the coast and along the north-south axis of Germany

» The cost delta between the two scenarios with grid expansion is only around 40 million €/a

When interpreting the results, it is important to note that grid expansion is carried out in “discrete” steps, meaning that an upgrade is needed when a line is overloaded regardless of whether the line is rarely and moderately or frequently and greatly overloaded. In the former case, the upgraded grid will have more “leeway” than in the later case.

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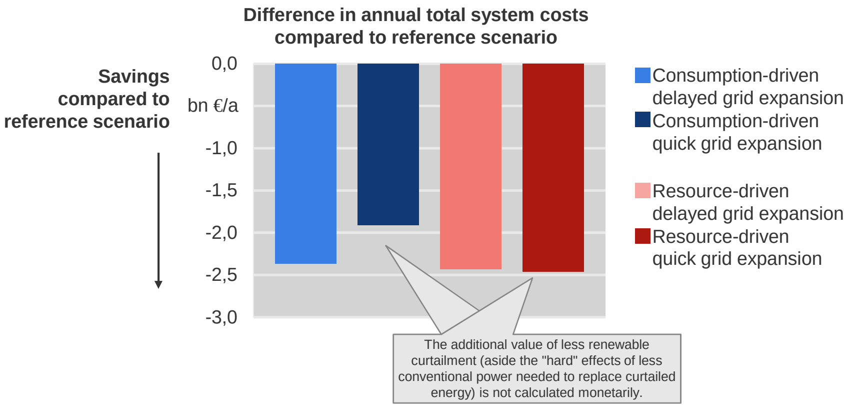
Cost comparison scenarios 2023

Summary comparison of all cost components



> Both alternative growth paths are around 2 to 2.5 billion €/a less expensive
» Savings mostly driven by lower investment costs in renewables (see above)

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Results 2033

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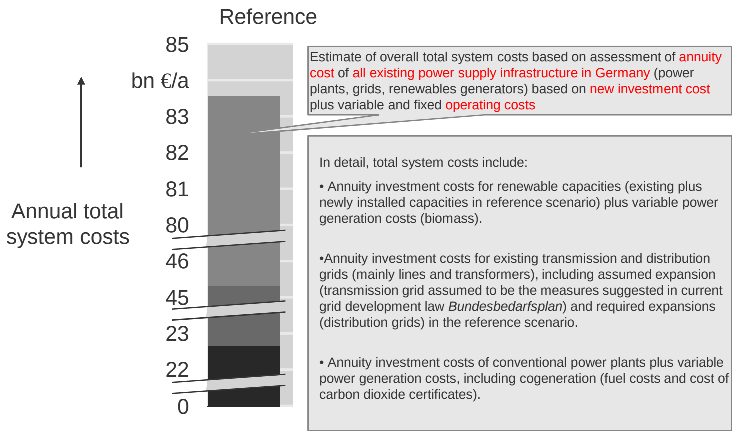
Cost comparison scenarios 2033

Starting point: annual total system costs in reference scenario



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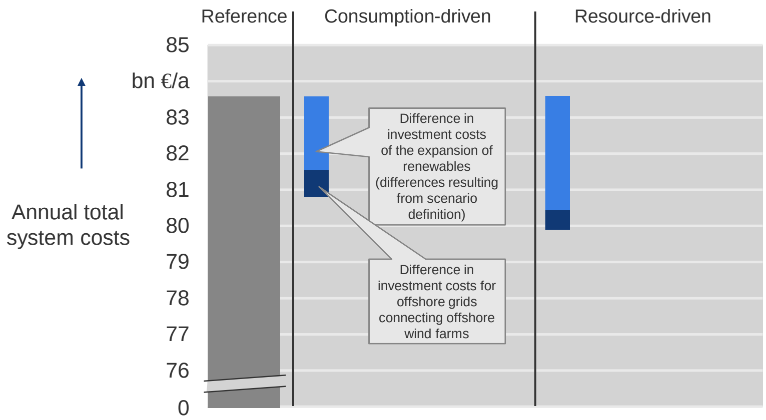
Cost comparison scenarios 2033

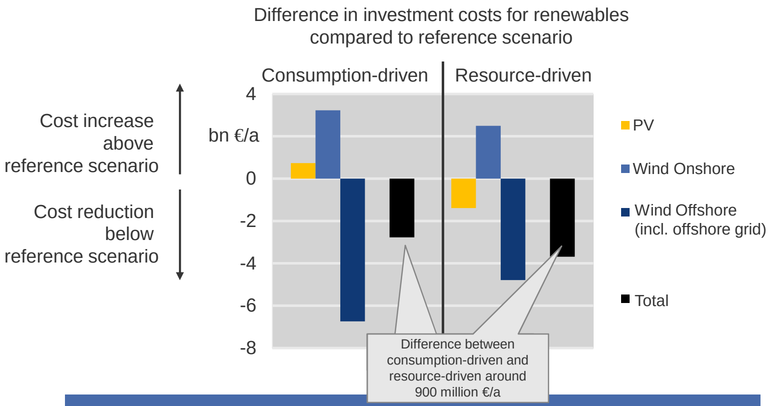
Cost differences for renewables growth



> Both alternative growth paths have lower costs for investments in new renewables for 2033

Cost comparison scenarios 2033

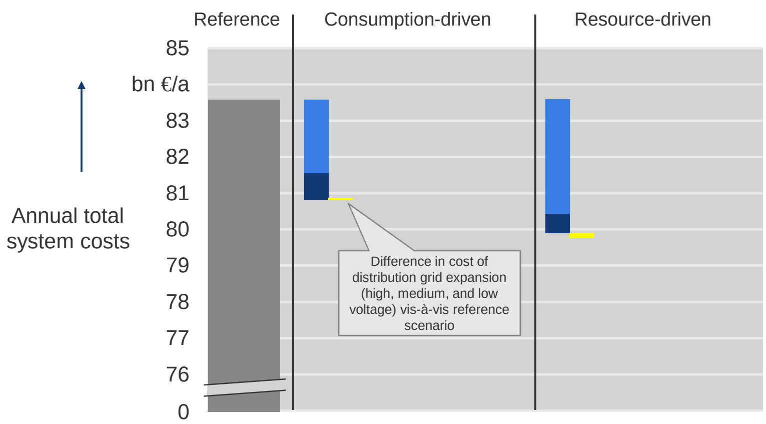
Detailed view on direct cost of renewables



> Effects largely comparable to 2023
- » Cost reduction in both scenarios below reference scenario still mainly driven by less offshore wind power

Cost comparison scenarios 2033

Cost differences for distribution grid expansion



> Cost difference in scenarios is relatively small, yet one is positive while the other is negative
- » Consumption-driven scenario ~70 million €/a more expensive than reference scenario
- » Resource-driven scenario ~130 million €/a less expensive than reference scenario

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Cost comparison of scenarios 2033

Detailed assessment of distribution grid expansion

- Consumption-driven scenario has highest costs of distribution grid expansion despite focus on proximity to consumption
  - Main reason: significant higher amount of installed renewable capacity (25 to 30 GW more than in other scenarios)
  - A closer look at specific costs (cost per MW) shows advantage of proximity to consumption
    - Specific expansion cost in consumption-driven scenario are ~ 2 Mio. €/GW/a lower than in resource-driven scenario

Annuity cost of distribution grid expansion above status quo per installed GW of capacity in distribution grids

- Cost savings in the resource-driven scenario compared to reference scenario are due to lower PV expansion (around 13 GW), and hence lower costs at low-voltage level

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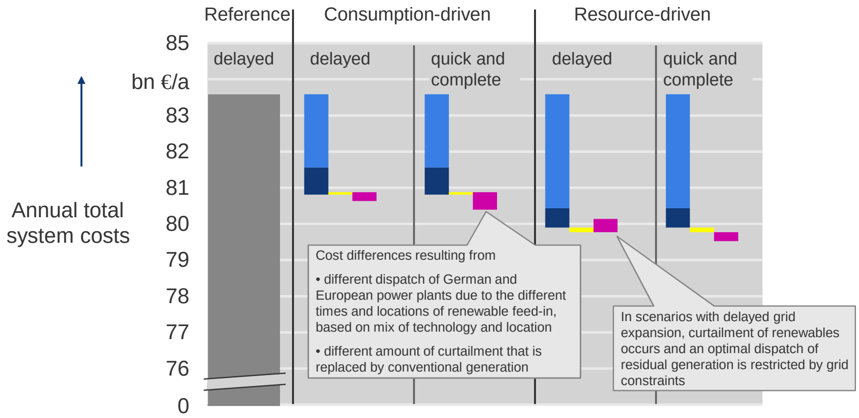
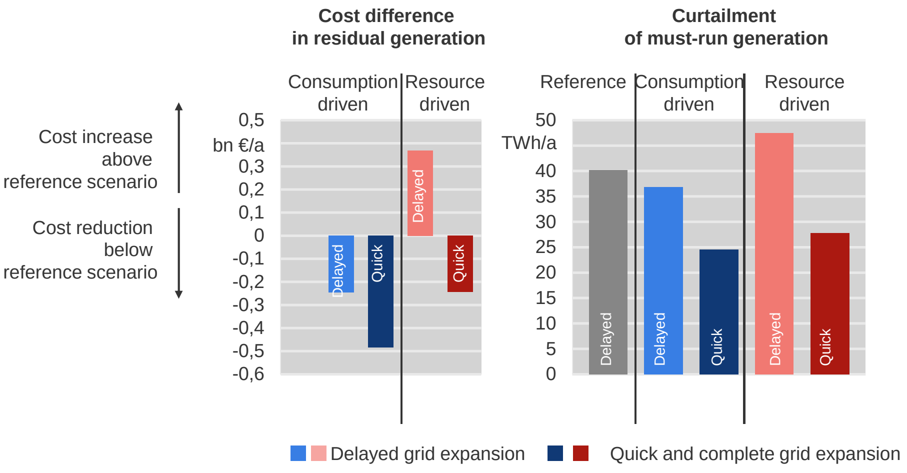
Cost comparison scenarios 2033

Cost differences in residual generation



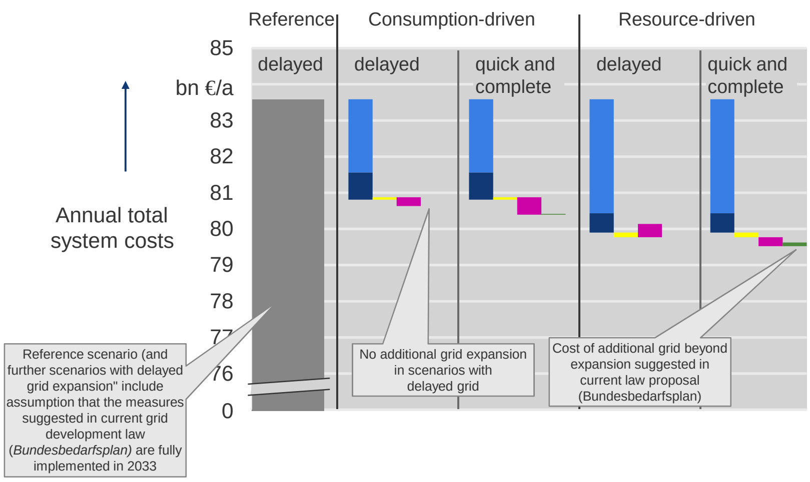
Scenarios 2033

Details of generation costs and curtailment



Cost comparison scenarios 2033

Cost differences: transmission grid expansion



Cost comparison scenarios 2033

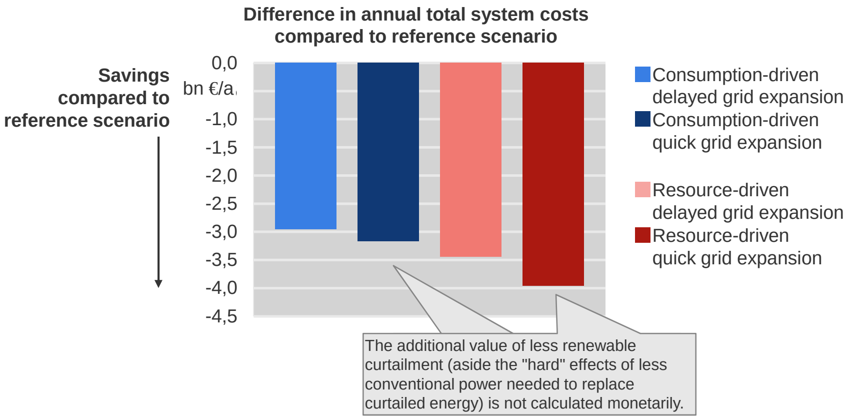
Detailed view on transmission grid expansion

- Even scenarios with delayed grid expansion assume a significant grid upgrade
- Assumed implementation of the measures of the current proposal of the grid expansion law (Bundesbedarfsplan) signifies a considerable grid expansion above the level of today and above the grid assumed to be in place in 2023 in the delayed grid scenario.

- Additional grid expansion requirements between 2023 and 2033 are in general far below those between 2013 and 2023 because the implementation of the current proposal of the grid expansion law (Bundesbedarfsplan) already accomplishes a significant adaptation of the German transmission grid to the fundamental shift of the location of power generation
- Additional need for grid expansion differs in the two scenarios with quick-and-complete grid expansion:
  - The consumption-driven scenario requires further upgrades in northwest Germany and centers of consumption in the southwest
  - The resource-driven scenario required in total a larger grid expansion
    - Especially along the coast, near load centers in western and southwest Germany, and in central Germany
  - The cost difference between the two scenarios with grid expansion is around 80 million €/a

Cost comparison scenarios 2033

Summary comparison of all cost components



- Both alternative growth paths are around 3 to 4 billion €/a less expensive

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Background information

Annex

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Investment cost of renewables

Assumptions on future investment costs per technology

> Assumptions on the investment cost of renewables are based on the lead study of the German ministry of environment[1] and were updated to recent market trends

Investment costs, EUR/kW	BMU Lead study	Adjustment of future cost development based on market trends[2]	Assumptions used:		
Year	2010		2013	2023	2033
PV rooftop arrays	2600	5 years earlier	1409	1051	959
PV ground-mounted arrays			1253	934	852
Wind onshore (low-wind sites)	1180	-	1168	1052	1032
Wind onshore (strong-wind sites)			957	931	853
Wind offshore (excluding offshore grid)	3500	3-year delay	3500	2200	1800

[1] http://www.dlr.de/dlr/Portaldata/1/Resources/documents/2012_1/leitstudie2011_kurz_en_bf.pdf

[2] Adjustments by Agora Energiewende; main sources used: PV: Photon Pricemonitor Solar plants, Fraunhofer ISE study on power generation costs (www.ise.fraunhofer.de/de/veroeffentlichungen/veroeffentlichungen-pdf-dateien/studien-und-konzeptpapiere/studie-stromgestehungskosten-erneuerbare-energien.pdf); offshore wind: Crown Estate Pathways Studie www.thecrownestate.co.uk/media/305094/ Offshore%20wind%20cost%20reduction%20pathways%20study.pdf); onshore wind: expert discussions, published costs od wind farms

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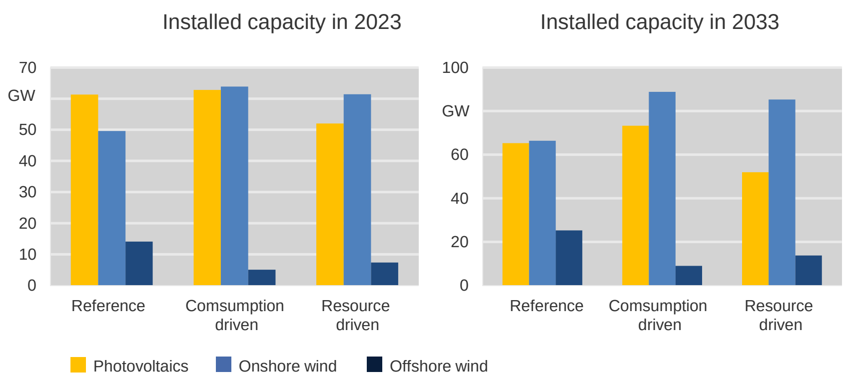
Assumptions on installed capacities of renewables

Scenario overview

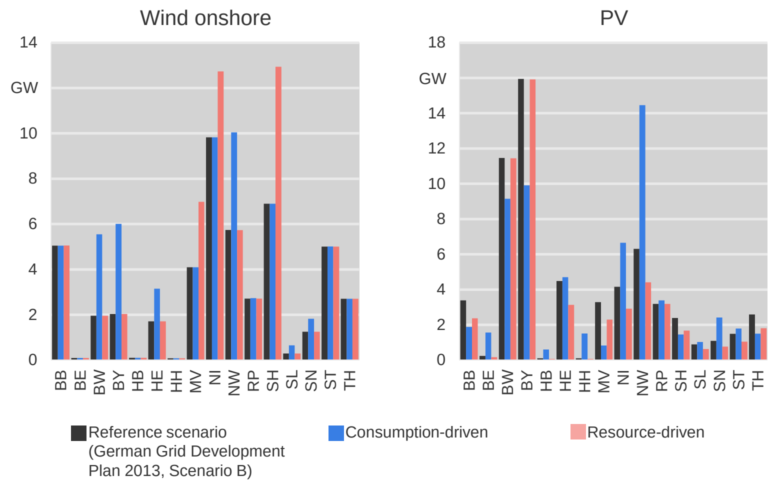
Installed capacities per technology in Germany in 2023 and 2033



Assumptions about installed renewable capacity

By German state

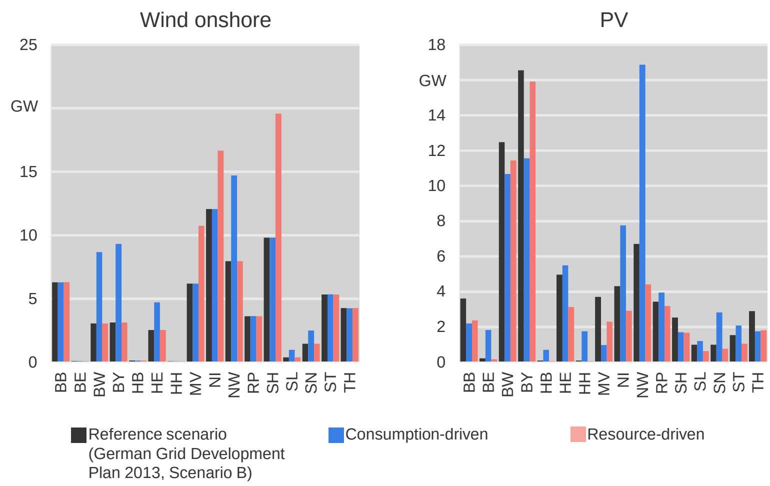
Installed capacities in German states (Länder) in 2023



Assumptions about installed capacity in renewables

Assessment by German Land

Installed capacities in German states (Länder) in 2033



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Approach and models used

Market simulation / generation

Determination of generation costs by market simulation

> Optimization variable: dispatch of all European hydro-thermal power plants
> Optimization target: minimize overall generation costs (only variable generation costs)
> Ancillary conditions: full coverage of residual load, grid constraints, technical restrictions, economic parameters (fuel costs, etc.)

Input:

- Power plants (entire EU)
- Power plant parameters (efficiency, etc.)
- Cost parameters (fuel cost, carbon prices, etc.)
- Time and location of feed-in of renewables and power consumption
- Commercial net transfer capacity of grids (NTC)

Optimization procedure:

Degrees of freedom: dispatch of conventional plants

Objective function: minimize generation costs across entire geographical area under review

Restrictions: full coverage of demand, NTC, storage basin restrictions, power plant flexibilities

Timeframe: one year on an hourly basis (8760h)

Optimization method: linear programming

Findings:

- Hourly power plant dispatch
- Cross-border trade
- Non-integratable must-run generation (curtailment)
- Generation costs (system-wide/country specific)

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Approach and models used

Grid simulation (transmission grid)

Grid model

> Use of an approximate data set of European transmission grid
  » Grid operation simulation requires model of European transmission grid down to single nodes and branches
  » Exact load flow models only available for TSOs and are not publicly available
  » Approximate data set based exclusively on freely available sources (such as grid maps, etc.) and is not subject to any usage restrictions
  » Applications have shown high correspondence with grid calculations based on exact data sets and a high suitability for principal investigations

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Approach and models used

Grid simulation (transmission grid)

Scenario variant: "quick and complete grid expansion"

Process of simulation of grid operation

> Results of market simulation are transferred to the grid model down to each node
> Carrying out of load flow and (n-1)-failure simulations for grid usage cases and review of loads on lines
> Results of simulation of grid operation:
  » In principle, load statistics for individual lines in transmission grid
  » In this study, identification of overloaded lines
  » Development of technically/economically appropriate grid expansion in load-flow model and renewed load flow/(n-1) grid security analysis
> Simulation of grid operation delivers the following main results:
  » Determination of demand for grid expansion
  » Determination of resulting costs

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Approach and models used

Grid simulation (transmission grid)

Scenario variant: "delayed grid expansion"

Flow of grid operation simulation

> Results of a "calibration calculation" of a market simulation are transferred to the grid model down to each node
  » Assumption: Germany as "copperplate"
> Carrying out of load flow and (n-1)-failure simulations for grid usage cases and review of loads on lines
> Results of simulation of grid operation:
  » In principle, load statistics for individual lines in transmission grid
  » In this study, identification of overloaded lines
  » Determination of additional grid-related constraints for a market simulation based on a regional model of Germany
> Renewed market simulation taking account of additional grid constraints
  » Resulting dispatch of power plants enables secure grid operation without inadmissible line overloads
  » Required re-dispatch of power plants is comparable across scenarios

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Approach and models used

Estimation of optimal amount of renewable curtailment in the distribution grid

Approach: incremental cost parity curtailment / distribution grid upgrade

- > Determination of specific grid upgrade costs
  - » Determination of interrelation between grid upgrade costs and “integration capacity" per grid level based on consideration of “model grids” and typical "classic“ approaches to grid upgrades
- > Analysis of the costs related to limiting the maximum feed-in of renewables
  - » Determination of typical interrelations between limits of maximum feed-in and the resulting amount of curtailment (based on IWES time series)
  - » Monetary assessment of amount of curtailment based on cost for renewable-feed-in
- > Determination of the break-even point of grid upgrade costs and curtailment cost
  - » The regional, technology-specific distribution of renewables (in accordance with scenario assumptions) determines the required integration capacity for distribution grid

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Approach and models used

Determination of the cost of distribution grid expansion

Determination of grid upgrade needed using model-grid analysis

- > Dimensioning of model grids (NE 3-7) below each high-voltage node
  - » High-voltage nodes represent the highest level of resolution in the assumptions for scenario definitions
  - » Consideration of specific requirements for power security and supply
    - > Area covered per grid level, number of buildings, and peak loads
    - > Number of renewable generators per grid level (typical size from TSO system registry, installed capacities per high-voltage node according to scenario definition)
    - > Individual density / spatial distribution of renewable generators depending on the number of renewable generators and loads connected
  - » Determination of load relevant for dimensioning per grid level and scenario
  - » Derivation of amount of grid expansion needed (NE 3-7)
    - > Per scenario and specific requirements for power security and supply
  - » Calculation of total cost for distribution grid upgrade per scenario based on amount needed and current average cost

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