# Exploring near-cost optimal alternatives for an inter-temporal model of the German power system

# Introduction

### What is done in this work?

* German energy system model parameters are defined for 2020, 2030, 2040 and 2050
* Model input parameters consists of ;
* Technical Parameters: Commodities, Commodity prices (€ /MWh), Maximum annual commodity use (MWh), Power generation technologies, Installed capacities of power generation technologies (MW), Reamining lifetime of installed capacities, Maximum allowed power throughput capacity per process, Economic lifetime of a process investment (years), process efficiencies(%), emission ratios(tons /MWh) , Storage technologies, Installed capacities (MWh) and/or installed power (MW) of storage technologies , Potential limit for storage energy/power capacities (MWh or MW), Input and output efficiencies for storage technologies, Economic lifetime of a storage investment (years), Self discharge rate per hour (%/h), Energy to power ratio for storage technologies (h), Electricity demand in hourly resolution (MWh), Capacity factors of regenerative technologies (Solar, Wind, Hydro, Geothermal)
* Economic Parameters: Discount rate(%), For each generation technology: Total investment cost for adding one MW capacity (€/MW), Annual fix cost per MW throughput power (operation independent yearly costs) (€/MW/a), Variable costs per MWh energy produced (Includes wear and tear of moving parts and operation liquids but excluding fuel costs) (€/MWh),   
  WACCafter-tax, real (weighted average cost of capital) (%), Investment fixed and variable cost per storage power capacity (units and scope as defined for generation technologies). Investment, fixed and variable cost per storage energy capacity; WACCafter-tax, real (%),
* Legislative Parameters: Annual CO2 Limit (tons)
* First defined model is optimized for minimum cost such a way that, hourly electricity generation will meet the hourly demand and yearly produced CO2 won’t exceed defined CO2 limit.
* For cost optimization an already existing linear optimization model for distributed energy systems is used. The model used is called URBS, it is open source it belongs to the Chair of Renewable and Sustainable Energy Systems, Technical University of Munich. Mathematical description of the model and detailed model equations are provided in model documentation, <https://urbs.readthedocs.io/en/latest/>.

#### Later the optimization problem is modified for "near cost optimal analysis". Minimum cost found from the previous optimization is set as a new constraint to the model with a small fractional increase. This small fractional increase is called slack value (ς) and varies between 1% -15%. Generation capacities of one or more generation technologies are defined as new objective function to the model. Capacities of specified generation technologies are first minimized and then maximized for the given ς value. Newly implemented model equations are explained in detail under Methodology section.

* Result of these two optimization shows us how sensible the expandability of the specified generation technology capacities to cost variations.
* It also shows us, how abstaining from or turning towards specific technologies will affect the outlook of Germany’s future energy system.

#### What are the objectives of your work?

In my work I aim to address non-monetary, hard to model policy driving factors that affects long term investment planning of German energy system.

In this work near cost optimal space of German energy system model is explored for next 30 years (till 2050). Deviation from cost optimum is done toward making model inclusive of social acceptance and political attitude towards different generating technologies.

This study aims to discover technologically diverse but similar costly investment paths. Concordantly also, how flexible the system reacts for different generation capacities in the same cost range.

This study aims to observe how energy system variate for different future load predictions.

Result of this study expected to show us;

a. What is the monetary cost of reaching environmental targets specified by the German government in order to achieve goals of Paris Agreement?

b. Essential and optional long-term investments policy decisions to meet predicted electricity demand while keeping up with environmental targets over the course of next 30 years.

c. how sensible the expandability of the specified generation technology capacities to cost variations.

d. how abstaining from or turning towards specific technologies will affect the outlook of future German energy system.

e. technologically diverse but similar costly investment paths for long term planning

What is novel?

What is the context of the work?

How does it contribute to energy policy literature?

What is the motivation and significance of your work?

Define your research question precisely:

Introduction to sections:

# Background (ONLY IF NECESSARY; MINIMUM AS POSSIBLE)

# Methodology

What is modeling to generate alternatives methodology?

What is near cost optimal space?

What is intertemporal model and what are the advantages of modeling intertemporally?

What is needed to be known for reproducing your work?

What existing frame work did you use?

What did you add; can you separate your work into sections?

Can you describe a methodology for each section of your work?

What are assumed parameters?

Based on what did you selected the data

## CO2 Limit / Budget for Germany

Legislation, statusco

## Policy Projections to 2050

Statusco in official documents

## Decommissioning of Nuclear and Coal Power plants

Statusco in official documents

## Optimization Logic:

### Extension to the model

# Data

### Economic Parameters

### Technical Parameters

### Time Series Parameters

### Modeled Processes

## Scenarios

### Demand

### CCS Implementation

## Data Availability

# Results and Discussion

What did you find?

Was that expected?

If yes how?

If no why?

Is it parallel with previous research?

# Conclusion and Policy Implications

# OUT OF PAPER EXTRAS

Multinode: making model inclusive of social acceptance and political attitude towards different generating technologies at different regions.

INPUT PARAMETERS   
\*SI decimal convention is used in this report. (‘.’ as decimal separator and ‘,’ as thousands separator)

Modelled Entities

Commodities

|  |  |
| --- | --- |
| Commodity | Type |
| Solar Energy | Intermittent supply commodity |
| Onshore Wind Energy | Intermittent supply commodity |
| Offshore Wind Energy | Intermittent supply commodity |
| Hydropower | Intermittent supply commodity |
| Geothermal Energy | Intermittent supply commodity |
| Electricity | Demand commodity |
| CO2 | Environmental commodity |
| Biogas | Stock commodity |
| Biomass | Stock commodity |
| H2 | Stock commodity |
| Natural Gas | Stock commodity |
| Hard Coal | Stock commodity |
| Lignite | Stock commodity |
| Uranium | Stock commodity |

Processes

|  |  |  |
| --- | --- | --- |
| Process Technology | Input Commodities | Output Commodities |
| Photovoltaic Panel | Solar Energy | Electricity |
| Onshore Wind Turbine | Onshore Wind Energy | Electricity |
| Offshore Wind Turbine | Offshore Wind Energy | Electricity |
| Hydroelectric Power Plant | Hydropower | Electricity |
| Geothermal Power Plant | Geothermal Energy | Electricity |
| Biogas Power Plant | Biogas | Electricity |
| Biomass Power Plant | Biomass | Electricity |
| Electrolyser | Electricity | H2 |
| Fuelcell | H2 | Electricity |
| Gas Turbine (GT) | Natural Gas | Electricity  CO2 |
| H2 | Electricity |
| Combined Cycle Gas Turbine (CCGT) | Natural Gas | Electricity  CO2 |
| H2 | Electricity |
| Hard Coal Power Plant (with and without CCS) | Hard Coal | Electricity  CO2 |
| Lignite Power Plant | Lignite | Electricity  CO2 |
| Nuclear Power Plant | Uranium | Electricity |

## GLOBAL PARAMETERS

|  |  |  |
| --- | --- | --- |
|  |  | Source |
| Discount Rate | 0.025 | [ECB IR] |
| CO2 Budget | See Scenarios for detailed information. | [DENA-2018] |
| Electricity demand | See Scenarios for detailed information. | [SMARD MD] [DENA-2018-] |
|  |  |  |

FULL LOAD HOURS

|  |  |  |
| --- | --- | --- |
| Type Of Energy | Full Load Hours (h/a) | SOURCE |
| Onshore | 1699,0456 |  |
| Offshore | 3220,6949 |  |
| Solar | 911,6078 |  |
| Geothermal | 8322,0000 |  |
| Hydro | 3261,0331 |  |

Process Parameters

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |
| PV | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs1 | Euro/MWout | 827,057 | 660,122 | 527,204 | 445,000 | [DYN DA] |
| Fixed Cost2 | Euro / MWout/a | 16,541 | 13,202 | 10,544 | 8,900 | [DYN DA] |
| Variable Costs3 | Euro / MWhout | 0 | 0 | 0 | 0 | [FRA-LCOE] |
| WACC4 | % | 2.1 | 2.1 | 2.1 | 2.1 | [FRA-LCOE] |
| Depreciation Period | years | 30\* | | | | [DENA-2018] |
| Initially installed capacity | MW | 49,550 | | | | [BMWi ZR][SMARD MD] |
| Potential Limit | MW | 250,000 | | | | [FRA ESD 50][FRA PV][DENA-2018] |
| Wind Onshore | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs1 | Euro/MWout | 1,100,000 | 957,000 | 911,000 | 865,000 | [DENA-2018][FRA- LCOE][PROG][AGORA 2050] |
| Fixed Cost2 | Euro / MWout/a | 30,000 | 19,140 | 18,220 | 17,300 | [FRA- LCOE] [AGORA 2050] |
| Variable Costs3 | Euro / MWhout | 5.00 | 5.0 | 5.0 | 5.0 | [FRA-LCOE] |
| WACC4 | % | 2.5 | | | | [FRA- LCOE] |
| Depreciation Period | years | 30\* | | | | [DENA-2018] |
| Initially installed capacity | MW | 53,405 | | | | [BMWi ZR][SMARD MD] |
| Potential Limit | MW | 200,000 | | | | [FRA 100][DYN DA][FRA ESD 50] |
| Wind Offshore | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs1 | Euro/MWout | 2,921,381 | 2,394,694 | 2,079,847 | 1,744,000 | DYN DA |
| Fixed Cost2 | Euro / MWout/a | 96,500 | 96,500 | 96,500 | 96,500 | DYN DA |
| Variable Costs3 | Euro / MWhout | 5.0 | 5.0 | 5.0 | 5.0 | [FRA- LCOE] |
| WACC4 | % | 4.8 | | | | [FRA-LCOE] |
| Depreciation Period | years | 30\* | | | | [DENA-2018] |
| Initially installed capacity | MW | 7,709 | | | | [BMWi ZR][SMARD MD] |
| Potential Limit | MW | 80,000 | | | | [FRA 100][DYN DA][FRA ESD 50] |
| Biomass (Solid,Liquid) | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs1 | Euro/MWout | 3,297,000 | 3,293,667 | 3,290,000 | 3,287,000 | DENA-2018 |
| Fixed Cost2 | Euro / MWout/a | 165,000 | 165,000 | 165,000 | 165,000 | DENA-2018 |
| Variable Costs3 | Euro / MWhout | 1.0\*\*\*\* | 1.0 | 1.0 | 1.0 | [FRA LCOE][PROG] |
| Efficiency | Elec\_out/ Biomass\_in |  |  |  | 0.3 | [DENA-2018] |
| WACC4 | % | 2.7 | | | | [FRA LCOE] |
| Depreciation Period | years | 30 | | | | [DENA-2018] |
| Initially installed capacity | MW | 1,868 | | | | [BMWi ZR] |
| Potential Limit | MWh | 200,000,000 | | | | [DENA-2018][Nach Biomass] |
| Biogas | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs1 | Euro/MWout | 3,843,370 | 3,767,816 | 3,678,954 | 3,658,000 | DYN DA |
| Fixed Cost2 | Euro / MWout/a | 249,819 | 244,909 | 239,132 | 237,806 | DYN DA |
| Variable Costs3 | Euro / MWhout | 1.0 | 1.0 | 1.0 | 1.0 | [FRA LCOE][PROG] |
| Efficiency | Elec\_out/ Biogas\_in | 0.35 | 0.37 | 0.38 | 0.40 | [FNR FZ] [UVE-Bıogas] [DYN-DA][DENA-2018] |
| WACC4 | % | 2.7 | | | | [FRA LCOE] |
| Depreciation Period | years | 30 | | | | [FRA LCOE][DENA-2018] |
| Initially installed capacity | MW | 7,051 | | | | [BMWi ZR] |
| Potential Limit | MWh | 50,000,000 | | | | [FRA 100] |
| Deep Geothermal Power plant | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs1 | Euro/MWout | 7,424,875 | 7,113,133 | 6,891,402 | 6,669,500 | DYN DA datenanhang 16,  IPCC TSC, Geo status report, Energie atlas bayern |
| Fixed Cost2 | Euro / MWout/a | 376,750 | 365,500 | 363,250 | 361,000 | DYN DA datenanhang 16 |
| Variable Costs3 | Euro / MWhout | 9.24 | 9.24 | 9.24 | 9.24 | [IPCC TSC] |
| Efficiency | Elec\_out/ Geothermal energy\_in | 0.11 | 0.12 | 0.13 | 0.14 | [DYN-DA] [HYDGEO] |
| WACC4 | % | 2.7\*\*\*\* | | | | [FRA LCOE] |
| Depreciation Period | years | 30 | | | | [DENA-2018] |
| Initially installed capacity | MWout | 48 | | | | [BMWi ZR] |
| Potential Limit | MW | 1,388\*\* | | | | [POT HGEO] [TAB Geothermie] |
| H2 Fuelcell | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs1 | Euro/MWout | 5,000,000 | 3,830,000 | 2,650,000 | 1,500,000 | [FUELCELL]  [H2-Compet] |
| Fixed Cost2 | Euro / MWout/a | 100,000 | 76,600 | 53,000 | 30,000 | Assumed as 2% of total investmet costs |
| Variable Costs3 | Euro / MWhout | 0.0 | 0.0 | 0.0 | 0.0 | Self-Assessment |
| Efficiency | Elec\_out/ H2\_in | 0.45 | 0.50 | 0.55 | 0.60 | [FNR FZ] [DOE FC] |
| WACC4 | % | 7.0 | | | | Self-Assessment |
| Depreciation Period | years | 10 \*\*\*\*\* | | | | [PEM -REW] and Self-Assessment |
| Initially installed capacity | MW | 0 | | | |  |
| Potential Limit | MW | Inf | | | |  |
| H2 Electrolyzer | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs1 | Euro/MWout | 815,000 | Stack:  276,000  System(except stack):  433,000 | Stack:  238,000  System(except stack):  366,000 | Stack:  200,000  System(except stack):  300,000 | [DENA-2018] [IRE-HYD] [P2G-Fınal] |
| Fixed Cost2 | Euro / MWout/a | 20,000 | 17,000 | 13,000 | 10,000 | [DENA-2018][IRE HYD][P2G FINAL] |
| Variable Costs3 | Euro / MWhout | 0.0 | 0.0 | 0.0 | 0.0 | Self-Assessment |
| Efficiency | Elec\_in /H2\_out | 0.82 | 0.83 | 0.83 | 0.84 | [DENA-2018] |
| WACC4 | % | 7.0 | | | | Self-Assessment |
| Depreciation Period | years | Stack: 10 years  System: 20 years | | | | [DENA-2018] [IRE-HYD] |
| Initially installed capacity | MW | 0 | | | |  |
| Potential Limit | MW | Inf | | | |  |
| Gas Turbine (GT)(Natural gas or H2) | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs1 | Euro/MWout | 540,000 | 496,250 | 452,500 | 408,750 | DYN DA DA  Fraunhofer LCOE  DENA-2018 (linear interpolation between years) |
| Fixed Cost2 | Euro / MWout/a | 18,000 | 15,600 | 13,200 | 10,800 | DYN DA DA  Fraunhofer LCOE  DENA-2018 (linear interpolation between years) |
| Variable Costs3 | Euro / MWhout | 3.0 | 3.0 | 3.0 | 3.0 | [FRA- LCOE] |
| Efficiency | Elec\_out/ Naturalgas\_in | 0.40 | 0.41 | 0.41 | 0.42 | [DYN-DA][DENA-2018] [MENA] |
| Elec\_out/ H2\_in | 0.40 | 0.41 | 0.41 | 0.42 | [H2 GTFuel] [H2-Compet] [SIE DS] |
| Emission Factor | Tons of CO2 /MWel\_out (Natural gas) | 0.50 | 0.49 | 0.49 | 0.48 | Calculated from 0.201 t/MWh\_th emission factor of natural gas. [UBA 16][AURORA] [UWBA web] [UWBA SCO2] |
| WACC4 | % | 5.2 | | | | [FRA- LCOE] |
| Depreciation Period | years | 30 | | | | [FRA LCOE][DENA-2018] |
| Initially installed capacity | MW | 13,142 | | | | [UBA KWL] [BDEW 2018] |
| Potential Limit | MW | Inf | | | |  |
| Combined Cycle Gas Turbine (Natural gas or H2) | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs1 | Euro/MWout | 900,000 | 866,000 | 833,000 | 800,000 | Fraunhofer LCOE, DYN DA DA, Prognose,DENA-2018, IPCC TSC |
| Fixed Cost2 | Euro / MWout/a | 28,000 | 28.666 | 29,334 | 30,000 | Fraunhofer LCOE, DYN DA DA, Prognose,DENA-2018, IPCC TSC |
| Variable Costs3 | Euro / MWhout | 4.0 | 4.0 | 4.0 | 4.0 | [FRA-LCOE] |
| Efficiency | Elec\_out/ Naturalgas\_in | 0.55 | 0.57 | 0.58 | 0.60 | [DYN-DA][DENA-2018] [MENA]  [TU DRESDEN VGT] |
| Elec\_out/ H2\_in | 0.58 | 0.59 | 0.59 | 0.60 | [H2 GTFuel] [H2-Compet] [SIE DS] |
| Emission Factor | Tons of CO2 /MWel\_out (Natural gas) | 0.370 | 0 | 0 | 0.335 | Calculated from 0.201 t/MWh\_th emission factor of natural gas. [UBA 16][AURORA] [UWBA web] [UWBA SCO2] |
| WACC4 | % | 5.2 | | | | [FRA- LCOE] |
| Depreciation Period | years | 30 | | | | [FRA LCOE][DENA-2018] |
| Initially installed capacity | MW | 18,570 | | | | [UBA KWL] [BDEW 2018] |
| Potential Limit | MW | Inf | | | |  |
| Hard Coal5 | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs1 | Euro/MWout | 1,500,000 | 1,500,000 | 1,500,000 | 1,500,000 | Fraunhofer LCOE, Prognose, DENA-2018 |
| Fixed Cost2 | Euro / MWout/a | 35,000 | 35,000 | 35,000 | 35,000 | Fraunhofer LCOE, Prognose, DENA-2018 |
| Variable Costs3 | Euro / MWhout | 5.0 | 5.0 | 5.0 | 5.0 | [FRA LCOE] |
| Efficiency | Elec\_out/ Hard coal\_in | 0.38 | 0.42 | 0.46 | 0.50 | [DENA-2018][MENA][FRA-LCOE] |
| Emission Factor | Tons of CO2/ MWel\_out | 0.89 | 0.80 | 0.73 | 0.67 | Calculated from 0.337 t/MWh\_th emission factor of hard coal. [UBA 16][AURORA] [UWBA web] [UWBA SCO2] |
| WACC4 | % | 5.6 | | | | [FRA- LCOE] |
| Depreciation Period | years | 40 | | | | [FRA LCOE][DENA-2018] |
| Initially installed capacity | MW | 22,458 (will be depreciated in 20 years) | | | | [SMARD MD] |
| Potential Limit | MW | No further expansions are considered | | | |  |
| Lignite5 | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs1 | Euro/MWout | 1,700,000 | 1,700,000 | 1,700,000 | 1,700,000 | Fraunhofer LCOE, Prognose, DENA-2018 |
| Fixed Cost2 | Euro / MWout/a | 40,000 | 40,000 | 40,000 | 40,000 | Fraunhofer LCOE, Prognose, DENA-2018 |
| Variable Costs3 | Euro / MWhout | 10.0\*\*\* | 10.0\*\*\* | 10.0\*\*\* | 10.0\*\*\* | [FFE MERIT] |
| Efficiency | Elec\_out/ Lignite\_in | 0.38 | 0.42 | 0.46 | 0.50 | [FRA LCOE][DENA-2018] |
| Emission Factor | Tons of CO2/ MWel\_out | 1.07 | 0.97 | 0.88 | 0.81 | Calculated from 0.407 t/MWh\_th emission factor of lignite. [UBA 16][AURORA] [UWBA web] [UWBA SCO2] |
| WACC4 | % | 5.6 | 5.6 | 5.6 | 5.6 | [FRA- LCOE] |
| Depreciation Period | years | 40 | | | | [FRA LCOE][DENA-2018] |
| Initially installed capacity | MW | 21,067(will be depreciated in 20 years) | | | | [SMARD MD] |
| Potential Limit | MW | No further expansions are considered | | | |  |
| Nuclear Powerplant6 | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs1 | Euro/MWout | 3,500,000 | 3,500,000 | 3,500,000 | 3,500,000 | [DENA-2018][IPCC TSC] |
| Fixed Cost2 | Euro / MWout/a | 109,000 | 109,000 | 109,000 | 109,000 | [IPCC TSC] |
| Variable Costs3 | Euro / MWhout | 8.0\*\*\* | 8.0 | 8.0 | 8.0 | [IPCC TSC] |
| Efficiency | Elec\_out / Uranium\_in | 0.33 | 0.33 | 0.33 | 0.33 | [DENA-2018][MENA] |
| WACC4 | % | 5.6 | 5.6 | 5.6 | 5.6 | Self-Assessment |
| Depreciation Period | years | 30 |  |  |  | [Nuclear lifetime] |
| Initially installed capacity | MW | 8,100 (will be depreciated in 2) | | | | [SMARD MD] |
| Potential Limit | MW | No further expansions are considered | | | |  |
| Hydropower (Run of the river or reservoir) | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs1 | Euro/MWout | 4,000,000 | 4,000,000 | 4,000,000 | 4,000,000 | [IPCC- TSC][DENA-2018] |
| Fixed Cost2 | Euro / MWout/a | 15,000 | 15,000 | 15,000 | 15,000 | [DENA-2018][IPCC TSC] |
| Variable Costs3 | Euro / MWhout | 0.0 | 0.0 | 0.0 | 0.0 | [IPCC TSC] |
| WACC4 | % | 2.7\*\*\*\* | | | | [FRA LCOE] |
| Depreciation Period | years | 100 | | | | [DENA-2018] [NREL Hydro] [ESU 2012] |
| Initially installed capacity | MW | 5,595 | | | | [BMWi ZR] |
| Potential Limit | MW | No further expansions are considered | | | | [FRA 100][DENA-2018] |
| CCS PC7 | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs | Euro/MWout | 3,500,000 | 3,150,000 | 2,835,000 | 2,551,500 | [IPCC- TSC][CCS COST] |
| Fixed Cost | Euro / MWout/a | 37,800 | 34,020 | 30,618 | 27,556 | [IPC- TSC] |
| Variable Costs | Euro / MWhout | 12.6 | 12.6 | 12.6 | 12.6 | [IPC- TSC] |
| Efficiency | Elec\_out/ Hard coal\_in | 0.32 | 0.32 | 0.32 | 0.32 | [IPCC TSC][CCS COST] |
| Emission Factor | Tons of CO2\_out / MWel\_out | 0.12 | 0.12 | 0.12 | 0.12 | [IPCC TSC][CCS COST] |
| Storage Factor | Tons of CO2 stored / MWel\_out | 0.77 | 0.68 | 0.61 | 0.55 | [IPCC TSC][CCS COST] |
| WACC | % | 7.0 | | | | Self-Assessment |
| Depreciation Period | years | 40 | | | | [IPC- TSC] |
| Initially installed capacity | MW | 0 | | | |  |
| Potential Limit | MW | Inf | | | |  |
| CCS IGCC7 | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs | Euro/MWout | 3,300,000 | 2,970,000 | 2,673,000 | 2,405,700 | [IPCC- TSC][CCS COST] |
| Fixed Cost | Euro / MWout/a | 19,320 | 17,388 | 15,649 | 14,084 | [IPC- TSC] |
| Variable Costs | Euro / MWhout | 11.0 | 11.0 | 11.0 | 11.0 | [IPCC- TSC] |
| Efficiency | Elec\_out/ Hard coal\_in | 0.32 | 0.32 | 0.32 | 0.32 | [IPCC TSC][CCS COST] |
| Emission Factor | Tons of CO2\_out / MWel\_out | 0.12 | 0.12 | 0.12 | 0.12 | [IPCC TSC][CCS COST] |
| Storage Factor | Tons of CO2 stored / MWel\_out | 0.77 | 0.68 | 0.61 | 0.55 | [IPCC TSC][CCS COST] |
| WACC | % | 7.0 | | | | Self-Assessment |
| Depreciation Period | years | 40 | | | | [IPC- TSC] |
| Initially installed capacity | MW | 0 | | | |  |
| Potential Limit | MW | Inf | | | |  |
| CCS Oxyfuel7 | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs | Euro/MWout | 3,900,000 | 3,510,000 | 3,159,000 | 2,843,100 | [IPCC- TSC][CCS COST] |
| Fixed Cost | Euro / MWout/a | 48,000 | 43,200 | 38,880 | 34,992 | [IPC- TSC] |
| Variable Costs | Euro / MWhout | 8.4 | 8.4 | 8.4 | 8.4 | [IPCC- TSC] |
| Efficiency | Elec\_out/ Hard coal\_in | 0.35 | 0.35 | 0.35 | 0.35 | [IPCC TSC][CCS COST] |
| Emission Factor | Tons of CO2\_out / MWel\_out | 0.08 | 0.08 | 0.08 | 0.08 | [IPCC TSC][CCS COST] |
| Storage Factor | Tons of CO2 stored / MWel\_out | 0.81 | 0.73 | 0.66 | 0.60 | [IPCC TSC][CCS COST] |
| WACC | % | 7.0 | | | | Self-Assessment |
| Depreciation Period | years | 40 | | | | [IPC- TSC] |
| Initially installed capacity | MW | 0 | | | |  |
| Potential Limit | MW | Inf | | | |  |
| CCS NGCC7 | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs | Euro/MWout | 1,600,000 | 1,440,000 | 1,296,000 | 1,166,400 | [IPCC- TSC][CCS COST] |
| Fixed Cost | Euro / MWout/a | 10,920 | 9,828 | 8,845 | 7,961 | [IPCC- TSC] |
| Variable Costs | Euro / MWhout | 7.0 | 7.0 | 7.0 | 7.0 | [IPCC- TSC] |
| Efficiency | Elec\_out/ Hard coal\_in | 0.47 | 0.47 | 0.47 | 0.47 | [IPCC TSC][CCS COST] |
| Emission Factor | Tons of CO2\_out / MWel\_out | 0.06 | 0.06 | 0.06 | 0.06 | [IPCC TSC][CCS COST] |
| Storage Factor | Tons of CO2 stored / MWel\_out | 0.31 | 0.30 | 0.29 | 0.29 | [IPCC TSC][CCS COST] |
| WACC | % | 7.0 | | | | Self-Assessment |
| Depreciation Period | years | 30 | | | | [IPC- TSC] |
| Initially installed capacity | MW | 0 | | | |  |
| Potential Limit | MW | Inf | | | |  |

\* In the considered sources depreciation periods of PV (photovoltaic), onshore wind and offshore wind technologies are specified as 25 years. However, model in this study is modeled with 10 years resolution, for that reason depreciation periods of technologies must be taken as multiples of 10 years. Any depreciation period value in between will be taken as floor division by 10 by model. (For example a PV technology that is built in 2020 will be depreciated in 2040 and therefore it won’t be utilized in the years between 2040 and 2046. However in reality, these technologies are often utilized more than their specified depreciation period[MaStr], for that reason 25 years of lifetime of specified technologies are rounded up to 30 years in the model.

\*\* Total technical electricity production potential of deep geothermal energy in Germany is calculated as 11.5 PWhel by [Potenziale der hydrothermalen geothermie]. For this total potential , a 1000 years of regenerative time frame is assumed. Which gives 11.5 TWhel/a regenerative technical potential. Since geothermal energy is modeled as intermittent supply commodity, capacity factor of the input flow is predefined by the user as timeseries in the input files.As capacity factor of the input commodity, therefore full load hours of the process is known, corresponding capacity of the geothermal power plant is calculated as 1,388 MW. For more information on intermittent supply commodities please refer to [Urbs docu/model implementation/parameters/technical parameters/commodity technical parameters]

\*\*\* This value for variable cost is taken to obtain correct marginal costs for conventional technologies in Germany [FFE MERIT]

\*\*\*\* Variable cost of biomass power plant is assumed same as the biogas power plant because those technologies have a similar operation procedure. Wacc value for biomass power plant and geothermal power plant assumed same with biogas power plant because renewable technologies assumed to have similar wacc values.

\*\*\*\*\*In literature [PEM REW] operation hours around 40,000h is estimated for stationary PEM fuelcell lifetime, this estimation is approximated to 10 years of operation)

1 Total investment cost for adding a MW of output capacity. It is annualized in the model using the annuity factor derived from ‘wacc’ and ‘depreciation’.

2 Operation independent annual costs for new and existing capacities per MW output power.

3 Variable costs per energy unit produced. Variable costs excludes fuel prices in this model.

4 Weighted average cost of capital (WACC). Percentage of costs for capital after taxes. It is used to calculate the annuity factor for investment costs in the model.

5 According to [kohlen ausstieg] coal power plant must be decommissioned by 2038. Considering this and 10 years modeling resolution, existing coal power plants are modeled to stay in production only till 2040 and no further expansion of these technologies is allowed. Only exception to this is CCS (carbon capture and storage) scenarios. In these scenarios, existing coal power plants will still be decommissioned by 2040 however; new coal power plants with CCS are allowed to be build.

6 According to [Nuclear ausstieg law] in Germany, all existing nuclear power plants will be decommissioned by 2022. For that reason no further extension of nuclear power plants are allowed, and due to the 10 years resolution of model, modeled existing nuclear technologies will not be utilized by the model.

7 CCS PC: Pulverized hard coal power plant with carbon capture and storage, CCS IGCC: Integrated combined cycle gasification hard coal power plant with carbon capture and storage, CCS Oxyfuel: Hard coal power plant with oxy-fuel combustion and carbon capture and storage, CCS NGCC: Natural gas combined cycle power plant with carbon capture and storage.

#### Commodity prices

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Commodity | Unit | 2020 | 2030 | 2040 | 2050 | Source |
| Natural gas | Euro/MWh\_th | 25.0 | 32.2 | 34.8 | 33.8 | [Fraunhocer LCO] |
| Hard Coal | Euro/MWh\_th | 11.1 | 13.4 | 15.2 | 15.2 | [Fraunhocer LCO] |
| Lignite | Euro/MWh\_th | 1.8 | 1.8 | 1.8 | 1.8 | [Fraunhocer LCO] |
| Uranium | Euro/MWh\_th | 0.88 | 0.88 | 0.88 | 0.88 |  |
| Biomass (Solid/Liquid) | Euro/MWh\_th | 21.0 | 23.0 | 25.0 | 27.0 | [PROGNOSE] |
| Biogas | Euro/MWh\_th | 25.0 | 26.0 | 27.0 | 28.0 | [PROGNOSE] |
| H2 | Euro/MWh\_th | 176.0 | 160.9 | 145.8 | 130.0 | [DENA-2018][Soner MT] |
| CO2 Storage | Euro/tons of CO2 | 7.0 | 7.0 | 7.0 | 7.0 | [CCS cost] |

Storage Techno-economic Parameters

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Pump Storage1 | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs Capacity | Euro/MWh\_storage\_capacity | 10,000 | 10,000 | 10,000 | 10,000 | [NIK SPA][ |
| Investment Costs Power | Euro/MW\_storage\_output\_power | 850,000 | 850,000 | 850,000 | 850,000 | [NIK SPA] |
| Fixed Cost Power | Euro/MW\_storage\_output\_power /a | 12,000 | 12,000 | 12,000 | 12,000 | [DENA-2018] |
| Efficiency\_in | MW\_stored/ MWel\_in | 0.85 | 0.85 | 0.85 | 0.85 | [FACT SHEET PSK] |
| Efficiency\_out | MW\_out/MW\_stored | 0.90 | 0.90 | 0.90 | 0.90 | [FACT SHEET PSK] |
| WACC | % | 7.0 | | | |  |
| Depreciation Period | years | 60 | | | | [NIK SPA] [Fraunhofer TES] DENA-2018 web] |
| Initially installed storage capacity | MWh | 37,389 | | | | [AKZU PUMP] |
| Initially installed output power | MW | 6,700 | | | | [DENA-2018 web] |
| Potential Limit | MWh  MW | 100,000  10,000 | | | | [NIK SPA] |
| H2 Storage2 | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs Capacity | Euro/MWh\_storage\_capacity | 450 | 450 | 450 | 450 | [NIK SPA] |
| Fixed Cost Capacity | Euro/MWh\_storage\_capacity /a | 15.75 | 15.75 | 15.75 | 15.75 | [NIK SPA] |
| Efficiency\_in | MW\_stored/ MWel\_in | 1.0\* | 1.0 | 1.0 | 1.0 | Self-Assertation |
| Efficiency\_out | MW\_out/MW\_stored | 1.0\* | 1.0 | 1.0 | 1.0 | Self-Assertation |
| WACC | % | 7.0 | | | |  |
| Depreciation Period | years | 40 | | | | [NIK SPA] |
| Initially installed storage capacity | MWh | 0 | | | | [FRA Wasserstoff] |
| Potential Limit | MWh | Inf | | | | [NIK SPA] |
| Battery Storage3 | Unit | 2020 | 2030 | 2040 | 2050 | Sources |
| Investment Costs Power | Euro/MW\_storage\_output\_power | 550,000 | 483,000 | 416,000 | 350,000 | [DENA-2018] |
| Fixed Cost Power | Euro/MW\_storage\_output\_power /a | 20,000 | 16,700 | 13,400 | 10,000 | [DENA-2018] |
| Energy to power ratio | hours | 4 | 4 | 4 | 4 | [Nikolaus Thesis] |
| Efficiency\_in | MW\_stored/ MWel\_in | 0.95 | 0.95 | 0.95 | 0.95 | [Fraunhofer TES] |
| Efficiency\_out | MW\_out/MW\_stored | 0.95 | 0.95 | 0.95 | 0.95 | [Fraunhofer TES] |
| WACC | % | 7.0 | | | | [Fraunhofer TES][DENA-2018] |
| Depreciation Period | years | 15 | | | | [DENA-2018] |
| Initially installed output power | MW | 0 | | | |  |
| Potential Limit | MW | Inf | | | |  |

[DYN DA]Dyamis Datenanhang

[DENA-2018]DENA-2018Ewi 2018

[FRA-LCOE]LEVELIZED COST OF ELECTRICITY RENEWABLE ENERGY TECHNOLOGIES March 2018 FRAUNHOFER INSTITUTE for Solar Energy Systems (2018)

[PROG]Prognose -Entwicklung von Stromproduktionskosten (2013)

[AGORA 2050] AGORA 2050 Energiewende kostenvergleich

[SMARD MD] SMARD MD Marktdaten https://www.SMARD MD.de markdaten visualisieren

[BMWi ZR]BMWi 2020 zeitreihe

[ECB IR]https://www.ecb.europa.eu/mopo/implement/sf/html/index.en.html

[FRA 100]Frauenhofer- 100 % ERNEUERBARE ENERGIEN FÜR STROM UND WÄRME IN DEUTSCHLAND Hans-Martin Henning, Andreas Palzer Fraunhofer-Institut für Solare Energiesysteme ISE

[FRA ESD 50](2050) SOW Frauenhofer

[FRA PV]Fraunhofer - PV

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[IRE-HYD]Irena Hydrogen from renewable power

[FUELCELL] Fuellcell applıcatıons for energy

[GEO-STA]Geothermal energy status report

[ENG-AT]https://www.energieatlas.bayern.de/thema\_geothermie/tiefe/daten.html

[IPCC- TSC]IPCCTechnology-specific Cost and Performance Parameters.pdf

[CCS COST] The cost of CO2 capture and storage

[P2G-Final]Power to gas fınal report

[H2-Compet]Path to hydrogen competetivenes (2020)

[FFE MERIT] <https://www.ffegmbh.de/aktuelles/veroeffentlichungen-und-fachvortraege/828-merit-order-der-konventionellen-kraftwerke-in-deutschland-2018>

[MaStR, 2020] Marktstammdatenregister <https://www.marktstammdatenregister.de/MaStR/Einheit/Einheiten/ErweiterteOeffentlicheEinheitenuebersicht>

[BA KWL]Kraftwerkliste bundesagentur [BA 2020 Kraftwerkliste]

[BDEW 2018]BDEW-Kraftwerkspark in Deutschland Aktueller Kraftwerkspark, Stromerzeugungsanlagen im Bau und in Planung, absehbare Stilllegungen konventioneller Kraftwerke Berlin, 27. April 2018

[IRE-HYD]Hydrogen from eRenewable power IRENA

DOE Fuelcell

[UBA KWL]Umweltbundesamt kraftwerkliste >100MW

[GEOTis, 2020]Geothermal information systems https://www.geotis.de/geotisapp/geotis.php [GEOTis, 2020]

[IPCC TSC]IPCC Technology specific costand

[FFE MERIT] FFE 2020, https://www.ffegmbh.de/aktuelles/veroeffentlichungen-und-fachvortraege/828-merit-order-der-konventionellen-kraftwerke-in-deutschland-2018

[NREL Hydro]- Hydropower

[ESU 2012]ESU 2012 hydroelectricity

[MENA] MENA-power generation systems

[UWBA web]Umweltbundersamt <https://www.umweltbundesamt.de/daten/energie/konventionelle-kraftwerke-erneuerbare-energien#kohlendioxid-emissionen>

[Aurora]Aurora-Studie-Strom-zu-Gas

[UBA 16]UBA 2016- CO2 Emission Factors for Fossil Fuels - Kristina Juhrich Emissions Situation (Section I 2.6) German Environment Agency (UBA) June 2016

[UWBA SCO2]Umweltbundesamt-climatechange-specific-c02-emissions

[FNR FZ]Fachagentur Nachwachsende Rohstoffe e. V. <https://biogas.fnr.de/daten-und-fakten/faustzahlen/>

[TU DRESDEN VGT]Vorlesung Gasturbinen GuD-Kraftwerke Fakultät für Maschinenwesen, Institut Energietechnik, Professur Kraftwerkstechnik TU Dresden]

[TAB Geothermie]Geothermie potential- Möglichkeiten geothermischer Stromerzeugung in Deutschland- Das Büro für Technikfolgen-Abschätzung beim Deutschen Bundestag (TAB)

[Nach Biomass]Nachhaltiges Biomassepotenzial für Deutschland

[POT HGEO]Potenziale der hydrothermalen geothermie

[FRA WASSERSTOF] Fraunhofer Wasserstoff roadmap

[Niko speich] Flexibilitätskonzepte für die Stromversorgung 2050- Peter Elsner | Manfred Fischedick | Dirk Uwe Sauer (Hrsg.)