
WindNODE_KWUM Documentation

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WindNODE KWUM is an energy system model for the Uckermark region.

1.1 Objective of the model

In regions with high RES shares, the RES electricity that cannot be transported off the grid or used by local consumers is regulated by the feed-in scheme (EinsMan), whereby theoretically producible RES electricity is lost unused¹. In addition, this unproduced “surplus” electricity is remunerated to the plant operators in the form of compensation payments. (see Figure 1.1). The resulting increase in the costs of the EinsMan is ultimately borne by the end consumer through higher grid usage fees (NNE)². Finally, a decreasing acceptance of the energy system transformation within the population is to be expected due to the rising costs, which could endanger the achievement of the climate targets in the long term³. In order to make better use of the existing capacities of the renewable energy plants, the “surplus” electricity could be stored temporarily on the one hand and used within other sectors (sector coupling) on the other⁴. However, it is above all the current regulatory framework with its system of taxes, network charges and allocations that prevents such use⁵. Against the background of the further decarbonisation of the energy sector via renewables, it is therefore necessary to reduce the regulatory aspects that hinder flexibility and to create incentives that enable a cost-efficient, secure and comprehensive integration of renewables⁶. This paper therefore aims to analyse the deployment potential of different flex options under three different regulatory frameworks.

¹ FATTLER, PICHLMAIER, ESTERMANN & OSTERMANN 2017, S. 59

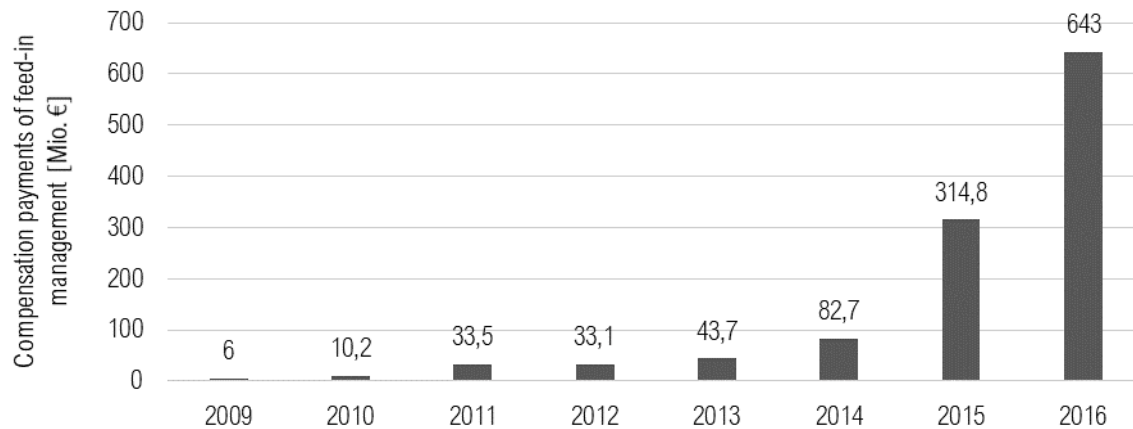
² FATTLER u. a. 2017, S. 57

³ KONDZIELLA u. a. 2019, S. 9

⁴ KONDZIELLA u. a. 2019, S. 11

⁵ SCHENUIT, HEUKE & PASCHKE 2016, S. 58; ZÖPHEL & MÜLLER 2016, S. 17

⁶ KONDZIELLA u. a. 2019, S. 34



Compensation payments caused by feed-in management measures in Germany

1.2 WindNode Project

In December 2016, the SINTEG funding programme was launched to undertake some of the challenges of the increasing share of electricity generated from renewable sources in the energy system. This programme is divided into five showcases regions; each of them has different goals and challenges. One of the five showcases is the WindNODE project, which takes place on the northeast of Germany, coincidentally with the area controlled by the transmission system operator 50Herzt (excluding Hamburg)⁷. The Reiner Lemoine Institute (RLI) is a partner of the joint research project WindNODE. The RLI participates in the analysis and comparison of two different regions: Uckermark and Anhalt. These research regions use different approaches for the integration of renewable energy, focusing on the use of flexibility options⁸. The research work of RLI in the Uckermark district is the analysis of business models of flexibility options; the estimation of the potential of the SINTEG-V regulation; and further possible regulations on the energy sector⁹. One wind farm operator in the Uckermark district is ENERTRAG AG, who is also part of the WindNODE project. This enterprise has provided some data used in this research paper.

1.3 Study Region in the Uckermark district

The Uckermark is a mainly rural region in the northeast of Brandenburg on the border to Mecklenburg-Western Pomerania. The population density of 67.68 inhabitants per km² is well below the Brandenburg average of 84.91¹⁰. The focus region under consideration is located in the north-eastern part of the Uckermark and covers 1470 km², about half of the Uckermark¹¹. The company Enertrag, the largest operator of wind turbines on site, provided the measurement data required for this investigation with regard to wind generation and control¹². Since their plants extend over the postcode areas around 16303, 16306, 16307, 17291 and 17326, the focus region was defined on this basis (see Figure 2.1).

⁷ BMWI 2019

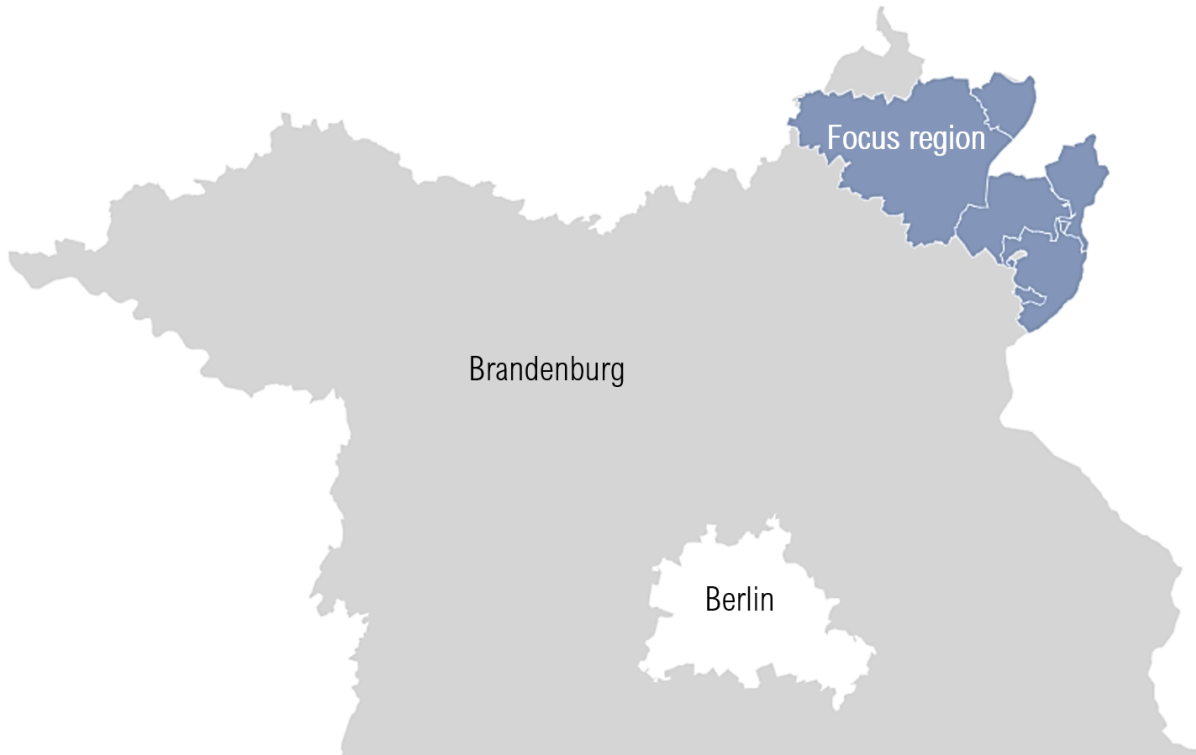
⁸ RLI 2019

⁹ RLI 2019

¹⁰ FAKTOR-I3 GMBH 2013, S. 3

¹¹ STATISTISCHE BUNDESAMT 2018

¹² ENERTRAG 2018



Geographical classification of the focus region

See *Quickstart* for the first steps. A deeper guide is provided in usage-details. We explain in detail how things are done in features-in-detail. *Input data and sources* details on how to import and suitable available data sources. For those of you who want to contribute see dev-notes and the *API* reference.

1.4 LICENSE

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2.1 1. Cloning the KWUM repository of Git-hub

- Link: https://github.com/windnode/WindNODE_KWUM/tree/dev

2.2 2. Download Scenario folders and integrate them in the KWUM-Project

Download the folders from the following link:

- Link: <https://next.rl-institut.de/s/6BZRiNjKjE2YkwD>

Integrate the folders one level above the KWUM project.

In each of the 27 scenario folders there is a file that starts with “sensi_param” in which the scenario variations can be selected. Here the capacities of the FlexOptions can be varied.

2.3 3. Calculate scenario files in oemof

- Run: `windnode_kwum/scenarios/!A_RUN_KWUM.py`

In this program, the previously defined scenario variations are created and calculated with the help of oemof to optimize operating costs. As a result, the program delivers the timeseries in the respective “results” folder.

2.4 4. Total cost and CO2 analysis of the calculated scenarios

- Run: `windnode_kwum/scenarios/!B_COST_CO2_ANALYSIS.py`

The previously calculated operating cost optimized timeseries are used to calculate the total costs and CO2 emissions. This evaluation takes place within Excel files, which are generated with the ending “_results” in the respective “results” folder. The most important key figures of the individual scenario variations calculated here are bundled in the Excel file “!_results_collection_...”. This makes it possible, for example, to quickly identify which scenario variation results in the lowest LCOH or the lowest CO2 emissions.

3.1 Basics of the Open Energy Model-ling Framework

In order to optimize the application possibilities of FlexOptionen in the context of the considered focus region in the Uckermark regarding the operating costs, the KWUM model was further developed based on the work of Romero Garcia 2018¹. This model was programmed on the basis of oemof² in Python. Within oemof different generic components can be linked:

- The component “Source” acts as an energy source, which is used in the KWUM model to generate wind power and to provide electricity and gas from the grid.
- Energy conversions are modelled via the component “Transformer”, with which CHP plants, heating plants, PtH and PtG are implemented.
- As soon as energy is consumed in the model or energy leaves the system, the “sink” component is used. These are used to model heat consumption, electricity sales and the regulation of the WTG.
- All components are connected via so-called “buses”, which serve as collection points and enable energy balancing.

All components, with the exception of the buses, can be equipped with capacity restrictions, time series and variable costs, whereby an energy system is finally created in oemof. Using the modelling framework “Pyomo”, the energy system thus created is formulated into a mixed integer problem, which is then solved by an external solver³ and leads to the generation of optimised feed-in time series and energy flows.

3.2 Model structure of the operational cost optimization

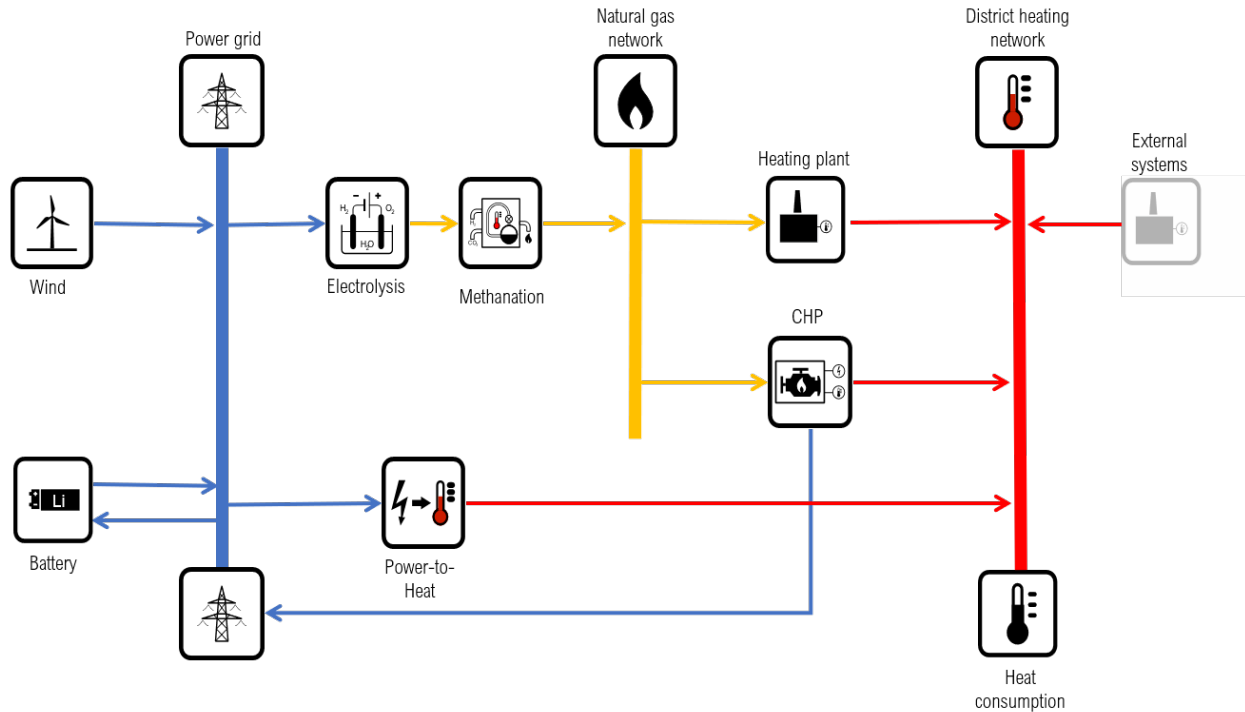
In order to cover the district heating demand, those systems are used which can generate the heat most cheaply at the respective time. This optimisation takes into account all labour-related costs and revenues of the individual plants. The investment costs of the plants, the power and capacity related electricity and gas procurement costs as well as fixed

¹ ROMERO GARCÍA 2018

² HILPERT u. a. 2018

³ The CBC Solver is Used in the KWUM Model

costs are not taken into account. These are recorded within the overall view (LINK!!!). A total of three power sources are available to the FlexOptions, which are associated with different procurement costs depending on the scenarios. This means that electricity can be obtained from the grid at any time at day-ahead market prices and scenario-dependent levies and allocations (grid electricity). On the other hand, so-called FlexStrom is available at certain times, which is defined on the basis of the criteria for grid and market serviceability of the SINTEG-VO⁴. FlexStrom is therefore electricity which would either have to be regulated out of the local wind turbines by one-man operations or which is available in the electricity grid at times of negative day-ahead market prices. In order to analyse potential synergies of PtH and PtG in connection with battery storage, these systems were additionally enabled to be supplied directly from the battery. The basic structure of the energy system under consideration and the integration of the Flex options are shown in the following figure. Modeling details can be found in ???.



Schematic model representation

3.3 Objective function

In the KWUM model, optimisation is achieved by minimising the annual operating costs of the individual components of the energy system. The target function to be minimized is therefore:

⁴ ALBERT, DODERER, MATTHES, SCHÄFER-STRADOWSKY & STEFFENSEN 2018, S. 51

$$\min \sum C_o(hp) + C_o(chp) + C_o(PtH) + C_o(PtG) + C_o(Batt) + C_o(St_{th})$$

$C_o(hp)$	annual operating costs of the heating plants
$C_o(chp)$	annual operating costs of the CHP plants
$C_o(PtH)$	annual operating costs of the power-to-heat systems
$C_o(PtG)$	annual operating costs of power-to-gas plants
$C_o(Batt)$	annual battery operating costs
$C_o(St_{th})$	annual operating costs of thermal storage facilities

3.4 Further modeling equations

Wind power generation and curtailment

The synthetic time series of the wind generation used in the model corresponds to the original generation measurement data $P_{el}(t, Wind_{using})$ outside the feed-in management inserts ($Curtailment=0$) and to the virtual generation load curve $P_{el}(t, Wind_{virt})$ within the control ($Curtailment>0$).

$$P_{el}(t, Wind_{synth}) = \begin{cases} P_{el}(t, Wind_{using}), & \forall t \in Curtailment = 0 \\ P_{el}(t, Wind_{virt}), & \forall t \in Curtailment > 0 \end{cases}$$

$$P_{el}(t, Wind_{curtailment}) = P_{el}(t, Wind_{using}) * Curtailment(t)$$

$$Curtailment(t) \in [0,1]$$

FlexStrom is defined in the model as wind power, which is either regulated by feed-in management applications or which is generated at times of negative day-ahead market prices. This FlexStrom can be used either by the FlexOptionen for storage or energy conversion or is otherwise curtailed ($P_{el}(t, curtailment)$).

$$P_{flexin}(t) = P_{el}(t, Wind_{curtailment}) + P_{el}(t, Wind_{negSpot})$$

$$P_{el}(t, Wind_{negSpot}) = P_{el}(t, Wind_{synth}), \quad \forall t \in C_{spot} \leq 0$$

$$P_{el}(t, curtailment) = P_{flexin}(t) - P_{flex}(t, PtH) - P_{flex}(t, PtG) - P_{flex}(t, Batt)$$

The costs of the FlexStrombezugs correspond to the Day-ahead market price, if this is negative at the time. Otherwise no costs result, since it concerns river, which would have to be abzuregeln in the reality.

$$C_{flex}(t) = \begin{cases} C_{spot}(t), & \forall t \in C_{spot} < 0 \\ 0, & \forall t \in C_{spot} > 0 \end{cases}$$

District heating demand

A central secondary condition states that the heat demand of the FW networks P_{th_demand} must be covered by the available heat generation plants in each time step.

$$P_{th_demand}(t) = P_{th}(t, hp) + P_{th}(t, chp) + P_{th}(t, PtH) + P_{th_out}(St_{th}) - P_{th_in}(St_{th}) + P_{th}(t, other)$$

heating plants

The operating costs of the heating plant consist of the procurement costs from the natural gas network C_{cs_gas} and the variable operating costs $C_{O\&M_var}$.

$$C_o(hp) = \sum_t P_{cs_gas}(t, hp) \cdot C_{cs_gas}(hp) + P_{th_out}(t, hp) \cdot C_{O\&M_var}(hp)$$

The heat generation of the heating plant P_{th_out} depends on the fuel input P_{Br_in} and the efficiency η_{th} .

$$P_{th_out}(t, hp) = P_{Br_in}(t, hp) \cdot \eta_{th}(hp)$$

The fuel input is made up of the two possible gas sources. This is the natural gas supply from the P_{cs_gas} gas network on the one hand and the synthetic natural gas supply from the PtG plant on the other.

$$P_{Br_in}(t, hp) = P_{cs_gas}(t, hp) + P_{PtG_Gas}(t, hp)$$

In addition to the pure natural gas costs K_{gas} , the purchase of gas from the grid is subject to CO2 charges K_{CO2} , energy taxes $K_{(E-Tax)}$, concession charges $K_{Konzess}$ and the working price of NNE $K_{(NNE_AP)}$. There are no costs for the purchase of synthetic natural gas. These are taken into account within the PtG plant.

$$C_{cs_gas}(hp) = C_{gas} + C_{CO2} + C_{E-Steuer} + C_{Konzess} + C_{NNE_AP}$$

CHP-Plant

The operating costs for CHP plants result from the following formula:

$$C_o(chp) = \sum_t P_{cs_gas}(t, chp) \cdot C_{cs_gas}(chp) + P_{el_out}(t, chp) \cdot C_{O\&M_var}(chp)$$

CHP plants generate revenue from the sale of electricity at (R_{base}), which is derived from the quarterly average baseload price of the EEX. This roughly corresponds to the market price for base-load electricity and is therefore more suitable as an input parameter for CHP plants than the more volatile day-ahead market price. In the model, the baseload price from the reference year 2016 is taken into account. On the other hand, operators of CHP plants receive a performance-related bonus (R_{bonus}) according to their electrical work fed into the grid.

$$R_O(chp) = \sum_t P_{elout}(t, chp) \cdot (R_{base}(t, chp) + R_{bonus}(chp))$$

In contrast to heating plants, CHP plants do not incur any CO2 costs or energy taxes.

$$C_{csgas}(chp) = C_{gas} + C_{Konzess} + C_{NNEAP}$$

$$P_{elout}(t, chp) = P_{Brin}(t, chp) \cdot \eta_{el}(chp)$$

$$P_{Brin} = P_{csgas}(t, chp) + P_{PtGGas}(t, chp)$$

$$P_{Brin}(t, chp) \leq P_{Brmax}(chp)$$

$$P_{Brmax}(chp) = \frac{P_{elout}(chp)}{\eta_{el}(chp)}$$

$$P_{thout}(t, chp) = P_{Brin}(t, chp) \cdot \eta_{th}(chp)$$

PtH plants

The operating costs of the PtH plants result from the following formulas:

$$C_O(PtH) = \sum_t P_{cs}(t, PtH) \cdot C_{cs}(t, PtH) + P_{flex}(t, PtH) \cdot C_{flex} + P_{el_{in}}(t, PtH) \cdot C_{O\&M_{var}}(PtH)$$

$$C_{cs}(t, PtH) = C_{spot} + C_{NNE_{AP}} + C_{EEG} + C_{Stromst} + C_{Konzess} + C_{CO2_{Handel}} + C_{CO2_{St}} + C_{KWKU} + C_{OffshoreU} + C_{AbschLU}$$

$$P_{el_{in}}(t, PtH) = P_{cs}(t; PtH) + P_{flex}(t, PtH)$$

$$P_{el_{in}}(t, PtH) \leq P_{el_{max}}(PtH)$$

$$P_{el_{max}}(PtH) = \frac{P_{th_{out}}(PtH)}{\eta_{th}(PtH)}$$

$$P_{th_{out}}(t, PtH) = P_{el_{in}}(t, PtH) \cdot \eta_{el}(PtH)$$

PtG plants

The operating costs of the PtG plants result from the following formulas:

$$C_O(PtG) = \sum_t P_{cs}(t, PtG) \cdot C_{cs}(t) + P_{flex}(t, PtG) \cdot C_{flex} + P_{el_{in}}(t, PtG) \cdot C_{O\&M_{var}}(PtG)$$

The payment obligation for NNE and the electricity tax does not apply to PtG.

$$C_{cs}(t, PtH) = C_{spot} + C_{EEG} + C_{Konzess} + C_{CO2_{Handel}} + C_{CO2_{St}} + C_{KWKU} \\ + C_{OffshoreU} + C_{AbschLU}$$

$$P_{el_{in}}(t, PtG) = P_{cs}(t; PtG) + P_{flex}(t, PtG)$$

$$P_{el_{in}}(t, PtG) \leq P_{el_{max}}(PtG)$$

$$P_{el_{max}}(PtG) = \frac{P_{gas_{out}}(PtG)}{\eta_{gas}(PtG)}$$

$$P_{gas_{out}}(t, PtH) = P_{el_{in}}(t, PtG) \cdot \eta_{el}(PtG)$$

Battery

The operating costs of the battery systems result from the following formulas:

$$C_O(Batt) = \sum_t P_{cs}(t, Batt) \cdot C_{cs}(t) + P_{flex}(t, Batt) \cdot C_{flex} + P_{el_{in}}(t, Batt) \\ \cdot C_{O\&M_{var}}(Batt)$$

In the model, batteries have the option of generating revenue by feeding electricity back into the grid.

$$R_O(Batt) = \sum_t P_{el_{cs_{out}}}(t, Batt) \cdot R_{spot}(t)$$

Heat storage The operating costs of the heat accumulator result from the following formulas:

$$C_O(St_{th}) = \sum_t (P_{th_{in}}(t, St_{th}) + P_{th_{out}}(t, St_{th})) \cdot C_{O\&M_{var}}(St_{th})$$

$$P_{th_{max}}(St_{th}) = \frac{C_{th}(St_{th})}{6}$$

Other heat generators

Those heat generators which are not substituted by flexibility options are considered separately. These include heat generation from biogas and sewage gas in Prenzlau and heat extraction from the PCK refinery and the waste inciner-

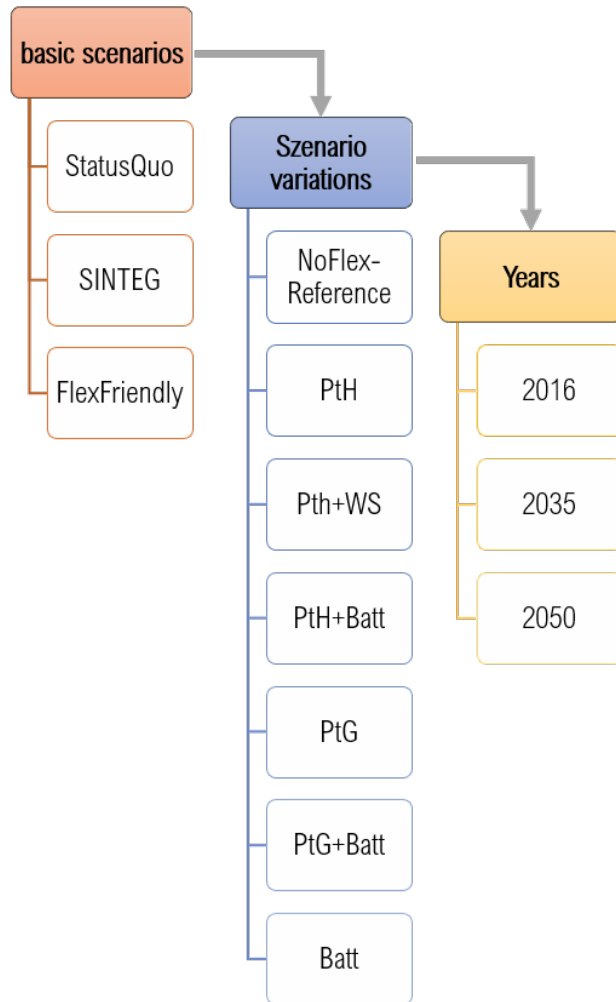
ation plant in Schwedt. Their relative heat input into the FW grid P_{th} (other) was determined as a time series using the reference scenario without FlexOptions and is assumed to be fixed for all other scenarios.

4.1 Variation of the regulatory frame-work

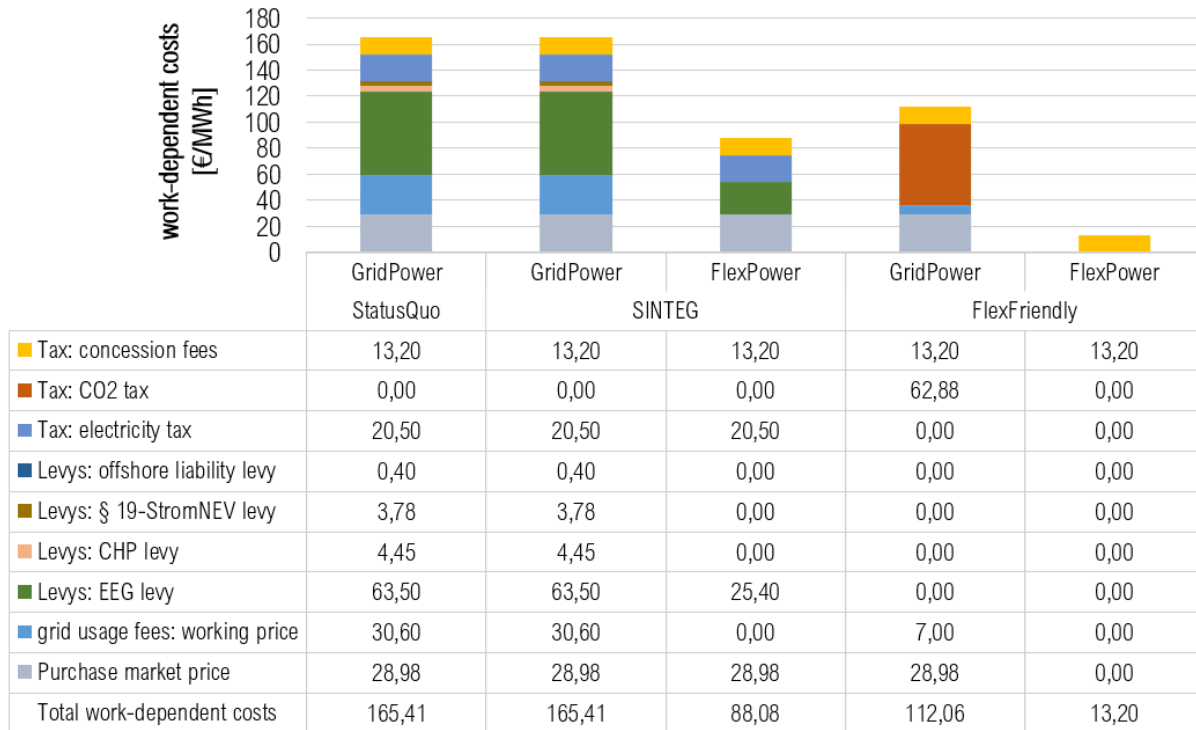
The three basic scenarios are divided into seven different scenario variations with regard to the flex options used. In the NoFlex variant, no FlexOptions are implemented, which means that this variant primarily serves as a reference on the basis of which the influence of the FlexOptions application is evaluated. In order to derive statements about possible future developments, all scenarios and scenario variations are examined for the years 2035 and 2050 in addition to the current status of 2016. These annual references are based on important transformation processes in electricity and heat supply¹, as well as on milestones of the climate targets². In the future, an increase in the supply of wind power is expected, including the amount of regulation, while the demand for heat will decrease due to the declining population and the increasing energy-efficient refurbishment. Furthermore, a rising gas price, rising NNE and a reduction of the EEG levy as well as different technology-specific development potentials are expected. The following figure shows the scenario structure once again schematically. This results in a total of 63 individual scenarios.

¹ STERNER & STADLER 2017, S. 141 ff

² BAUKNECHT u. a. 2016



The status quo scenario represents the current regulatory framework. In the SINTEG scenario, the distinction made in the SINTEG Regulation between grid and market electricity purchases and general electricity purchases is applied. In the KWUM model, this is illustrated by a differentiation between the unrestricted purchase of “grid electricity” and “FlexStrom”, which depends on the EinsMan and the negative day-ahead market price. In the parameterisation of the FlexFriendly scenario, the reform approaches with regard to the integration of capacity-related price components at the NNE and the introduction of cross-sector CO₂ pricing were taken up. In this scenario, the price for the purchase of electricity from the grid consists only of the exchange price, the concession fees and the NNE. The working price of the NNE has fallen significantly as a result of an increase in the performance- and capacity-related price components. The largest cost factor for grid electricity procurement in 2016, at 56 %, is the cross-sector CO₂ pricing. In the year 2050, however, due to the assumed strong reduction of the CO₂ emission factor of the electricity mix, this only has a share of 22 %. Furthermore, it is assumed that Flex electricity can be purchased at no cost at EinsMan times due to its systemic nature, and at the current negative costs at times of negative exchange prices.



4.2 Variation of the used technologies

As technical flexibility options, both storage and sector coupling technologies are examined in relation to the existing heat networks. The decentralised heat demand and the mobility sector are not the subject of this work. In the coupling of the electricity sector with the (central) heat sector, PtH in particular, especially in combination with a heat accumulator, has emerged as a rapidly accessible key technology for the substitution of fossil fuels³. Another possibility for electrifying the heating sector in the medium term is attributed to PtG⁴. In combination with a subsequent methanation unit for the production of synthetic methane, the natural gas network can act as a gas storage facility and thus contribute to the flexibility of the PtG plant. This makes PtG one of the most suitable technologies for long-term storage⁵ and is also the subject of this study. In addition to the heating sector, the excess FlexStrom can also be used within electricity storage facilities. Pumped storage power plants, compressed air reservoirs and batteries, for example, are suitable for this purpose. While the geographical conditions for the construction of pumped storage power plants and compressed air reservoirs in the Uckermark are not favourable⁶, batteries can be installed flexibly and independently of location. Batteries are currently still characterized by very high specific costs⁷, but very high cost degression is expected in the future, especially for lithium-ion batteries⁸ and are also well suited to absorb the negative consequences of fluctuating feed-in of renewables in the low and medium voltage ranges⁹. Possible synergy effects in connection with the considered sector coupling technologies PtH and PtG are also analyzed. Particularly in the future, favourable battery options could increase the utilisation of very investment-intensive technologies such as PtG or reduce their electricity procurement costs and thus indirectly contribute to the electrification of the heating sector.

³ AGORA ENERGIEWENDE 2017, S. 134; BECHEM u. a. 2015, S. 125; GERHARDT u. a. 2015, S. 106

⁴ KUPRAT 2017, S. 2; STERNER & STADLER 2017, S. 150

⁵ DEUTSCHER BUNDESTAG 2015, S. 16

⁶ MANN u. a. 2013, S. 124

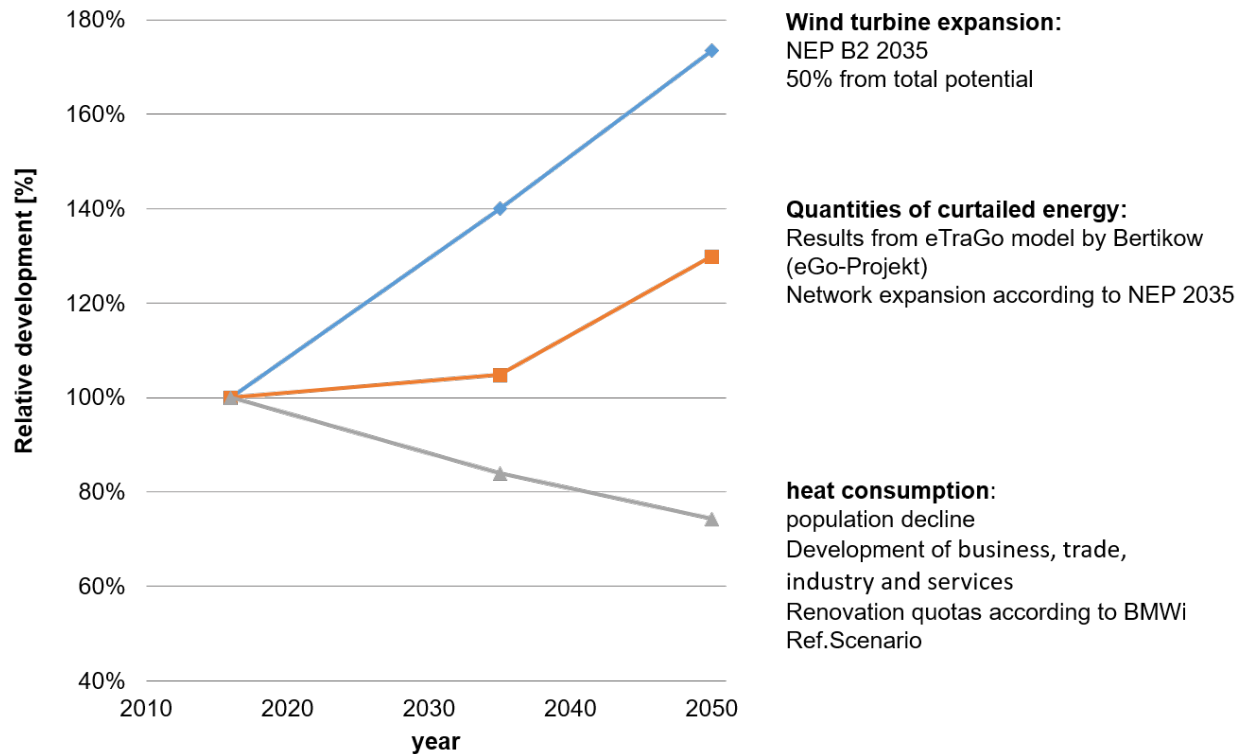
⁷ WIETSCHEL, ULLRICH, MARKEWITZ & SCHULTE 2015, S. 208

⁸ KRZIKALLA, ACHNER & BRÜHL 2013, S. 67

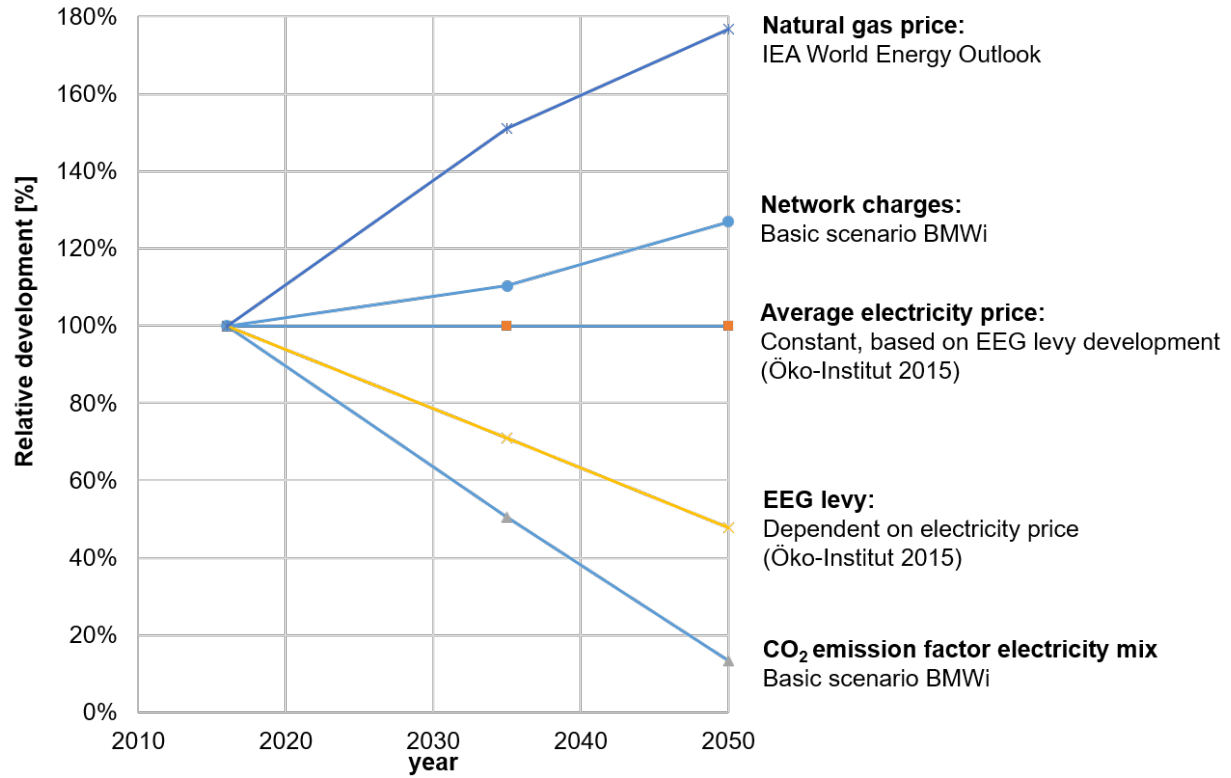
⁹ AUNDRUP, BECK & BECKER 2015, S. 8

4.3 Assumptions for the development in the future

The following figures show the assumptions made in the model with regard to regional and supra-regional future developments.



Development of regional model parameters



Development of supra-regional model parameters

Input data and sources

Electricity production

The power plant list of the Federal Network Agency¹ gives an overview of the structure of power generation plants larger than 10 MWel. In total, 962 MW of electrical power is generated in the focus region, 62 % of which comes from renewable sources (mainly wind energy). The remaining 38 % are generated by the incineration of waste and refinery gas residues, which are limited to the industrial location of Schwedt. The following table shows the generation capacities by energy source and postal code within the focus region.

Postcode areas of the Focus region	Waste	Biomasse	Mineral oil products	PV	Wind power	Total
16303	28.900	2.760	333.500	13.614	64.580	443.354
16306		0.605		9.399	114.995	124.999
16307		0.250		5.094	28.000	33.344
17291		11.947		43.646	457.035	512.628
17326		0.250		0.508	52.900	53.658
Total	28.900	15.812	333.500	72.261	717.510	1167.983

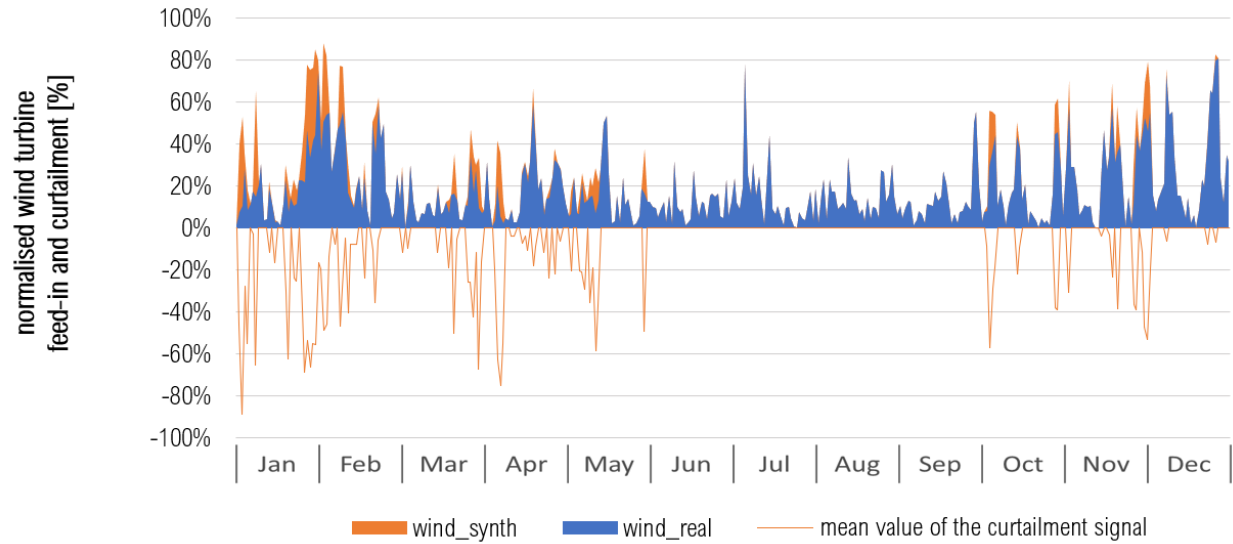
Capacity of power generation plants in MW by energy source and postcode in the focus region²

5.1 Timerows of generation and curtailment of the wind turbines

In the following figure, the normalized real (blue) and synthetic (orange) generation load curves are plotted as areas over the year and the deviation signal (orange line). The visible orange area indicates the curtailed part of the wind power work that is available to the FlexOptions within the KWUM model. In total, this percentage is 14.33 % of the synthetic wind power work which is adjusted from the curtailment.

¹ BNETZA 2018

² Own representation according to 50 HERTZ 2018; BNETZA 2018



Normalised real and synthetic wind feed-in from Bertikow transformer station and curtailment signal in 2016 as daily averages³

It is difficult to make any assumptions about the future development of the scheme and they depend on a large number of factors which affect both the capacity utilisation of the transmission and distribution networks. In principle, grid expansion after the NEP contributes to a reduction in grid bottlenecks. Due to the peak capping and the time delay of the grid expansion, feed-in management can also be expected in the future. Since no detailed modelling of the electricity grid can be realised within the KWUM model, assumptions must be made here on the basis of other sources of information. For this purpose, data from the eTraGo project, in which the German transmission and distribution grid was modelled and grid simulations for the future carried out on the basis of the NEP scenarios, are used⁴. With this model it is possible to simulate the future development of the feed-in and control behaviour in the individual substations between transmission grid and distribution grid. The Flensburg University of Applied Sciences therefore requested a data set⁵ for the feed-in and regulation of the Bertikow substation, of which real reference time series for feed-in and regulation already exist⁶.

Since no further plans for further grid expansion have been made so far and a continuation of the regulation is to be expected⁷, the same percentage of regulation of 10.77 % is assumed for the year 2050 which, in connection with the further increase in generation capacity, will result in an absolute increase in the regulation work.

	2016	2035	2050
Potential generation <u>synth_pot</u> [MWh]	1,324,287	1,853,891	2,296,753
Share of <u>curtailment</u> [%]	14.33 %	10.77 %	10.77 %
Absolute <u>curtailed work</u> [MWh]	190,610	199,695	247,399

Generation and curtailed quantities of wind turbines in the focus region⁸

³ Own representation according to ENERTRAG 2018

⁴ MÜLLER u. a. 2018, S. 1

⁵ MÜLLER 2018

⁶ ENERTRAG 2018

⁷ KONDZIELLA u. a. 2019, S. 18

⁸ Own representation

5.2 Thermal plants in the district heat-ing systems

For the future scenarios, it is assumed that FW consumption will be reduced by 2050 due to population decline and energy-efficient refurbishment. In order to avoid an unrealistic over-dimensioning of the plant park in the future, it is assumed that the plant capacities will be reduced in line with the expected FW consumption.

Heat production plants	2016	2035	2050
CHP EE Prenzlau [MW _{th}]	2.778	1.925	1.330
CHP Prenzlau [MW _{th}]	0.550	0.381	0.263
Heating plant Prenzlau [MW _{th}]	22.872	15.848	10.951

Development of the thermal capacities of the heat generation plants in Prenzlau⁹

Heat production plants	2016	2035	2050
CHP_ee_sch [MW _{th}]	18,398	12,748	8,809
CHP Schwedt [MW _{th}]	0,452	0,313	0,216
Heating plant Schwedt [MW _{th}]	40,270	27,903	19,281

Development of the thermal capacities of the heat generation plants in Schwedt¹⁰

5.3 Timerows of the district heat demand

The “demandlib” from the oemof framework was used to generate the district heating load profile¹¹. The theoretical calculation bases are based on the work of Hellwig 2003¹² and the further development according to BGW 2006¹³. The derivation of the input data relevant for load profile generation is described below.

- The annual space heating requirements of the household and GHD sectors are derived on the basis of Factor i3 2013. District heating consumption in Prenzlau is 25,400 MWh and for Schwedt 122,733 MWh¹⁴.
- Furthermore, the structure of the building with regard to type and age of the building is decisive for the construction of the heat load corridor. Older and small single-family houses tend to have a higher specific heat consumption than new multi-family houses. From the 2011 census data, both the age structure and the type of building can be derived as a function of the number of flats in buildings with FW connections per municipality¹⁵.
- The temperature measurement time series for 2016 was taken from the Climate Data Center of the German Weather Service¹⁶. The station Grünow was chosen as the temperature reference location due to its central location within the focus region. It is located about 5 km west of Prenzlau with the coordinates: 53.3153 N 13.9338 W.
- The building age classes are determined on the basis of the census data according to the BGW 2006¹⁷ method. The buildings in the FW-Netz Prenzlau are assigned to age group 6 and Schwedt to age group 5.

⁹ Own representation

¹⁰ Own representation

¹¹ OEMOF DEVELOPING GROUP 2018

¹² HELLWIG 2003

¹³ BGW 2006

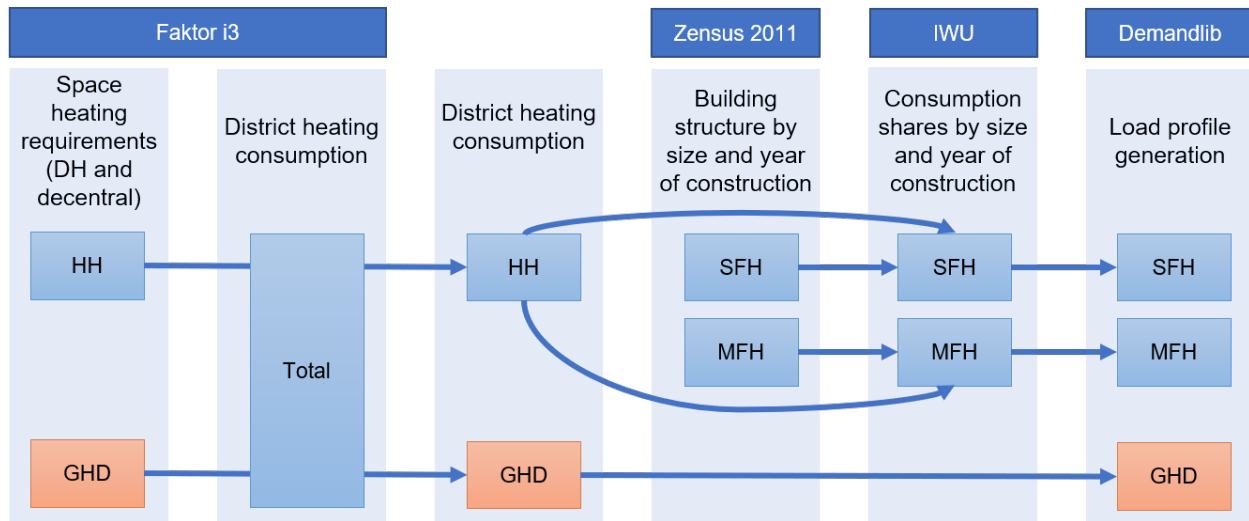
¹⁴ FAKTOR-I3 GMBH 2018

¹⁵ ZENSUS 2011 2011

¹⁶ DEUTSCHER WETTERDIENST 2018

¹⁷ BGW 2006, S. 42

The methodical procedure as well as the sources used for the compilation of the FW load profiles are shown in the following figure.



Procedure for generating the FW consumption load profiles¹⁸

Within the model, heat losses are taken into account indirectly by adding them evenly to consumption throughout the year¹⁹. In Prenzlau, 14.00 % network losses are assumed²⁰, in Schwedt 18.34 %²¹. The maximum consumption in the respective heating network can be derived from the generated heat load profiles. This results in a peak load of 11.461 MWth in Prenzlau and 47.397 MWth in Schwedt, which is comparable to the real peak heat load of 52.000 MWth²² in 2016. For the Prenzlauer FW network, however, there are no comparable values available.

¹⁸ Own presentation; sources used: FAKTOR-I3 GMBH 2018; LOGA, STEIN, DIEFENBACH & BORN 2015; OEMOF DEVELOPING GROUP 2018; ZENSUS 2011 2011

¹⁹ KONSTANTIN 2018, S. 32

²⁰ B.B.S.M. 2013, S. 31

²¹ STADTWERKE SCHWEDT GMBH 2018

²² STADTWERKE SCHWEDT GMBH 2017

6.1 Anlagenspezifische annuitätische Gesamtkostenbetrachtung

The economic valuation of the individual plants is carried out by determining the annual costs and revenues. Usually, the annuity method (according to VDI 2067)¹ is used, in which financial variables such as interest rates, inflation and price changes are taken into account as a dynamic method. The total annual costs (capital costs, operating costs, electricity and gas costs incl. NNE, levies and charges) as well as the proceeds from electricity sales (for CHP plants and batteries) are distributed evenly over the 30 year period under consideration. If a plant is not used within the scenarios, it is assumed that it will not be implemented in this case either, so that in this case all costs of the plant are omitted. The annuity (AN_i) is calculated as follows:

$$AN_i = AN_{C_i} + AN_{V_i} + AN_{O_i} - AN_{R_i}$$

AN_{R_i} Annuity of revenues

AN_{C_i} Annuity of capital costs

AN_{V_i} Annuity of demand-driven expenditure

AN_{O_i} Annuity of operating expenditure

Capital-linked payments

¹ VDI 2013

$$AN_k = \left(A_0 + \sum_{k=1}^n A_k - R \right) \cdot a$$

AN_k	Annuity of capital-bound costs
A_0	Initial investment amount in €
A_k	Present value of the k -th replacement purchase in €.
n	Number of replacement purchases
R	Present value of the residual value in €
a	Annuity factor

The assumed equity interest rate (i_{EK}) for district heating networks is 10 % and the assumed debt interest rate (i_{FK}) is 4 %. An equity share of 20 % results in a calculation interest rate (i_{calc}) of 5.2 %² and thus an interest factor (q) of 1.052. The inflation rate (j) is assumed to be 2.3 % after³, resulting in a price change factor (r) of 1.023. A period (T) of 30 years is considered, from which an annuity factor (a) of 0.06654 results in connection with the calculatory interest rate i_{calc} .

$$a = \frac{(1 + i_{Kalk})^T \cdot i_{Kalk}}{(1 + i_{Kalk})^T - 1}$$

a	Annuity factor
i_{Kalk}	Calculation interest
T	Period under consideration

<i>calculation interest i_{Kalk}</i>	5.2 %
<i>rate of inflation j</i>	2.3 %
<i>interest factor q</i>	1.052
<i>price change factor r</i>	1.023
<i>Considered period T</i>	30
<i>annuity factor a</i>	0.066541979
<i>Price dynamic present value factor for capital costs b_K</i>	19.58

assumed parameters for capital expenditure under the annuity method

If the assets have to be replaced within the period under consideration (T) due to their lifetime, the present value of these replacements is calculated according to the following formula and is also taken into account within the capital-linked disbursements.

² DUNKELBERG, GÄHRS, WEIß & SALECKI 2018, S. 79

³ DUNKELBERG u. a. 2018, S. 35

$$A_k = A_0 \cdot \frac{r^{k \cdot TN}}{q^{k \cdot TN}}$$

TN	Useful life of the asset
r	price change factor
q	interest factor
k	k-th replacement procurement

If the lifetime of the installation exceeds the period under consideration, the residual value of the installation is taken into account using the following formula.

$$R = A_0 \cdot r^{n \cdot TN} \frac{(n+1) \cdot TN - T}{TN} \cdot \frac{1}{q^T}$$

R	residual value
A_0	Initial investment amount in €
A_k	Present value of the k-th replacement purchase in €.
n	Number of replacement purchases
R	Present value of the residual value in €
a	annuity factor
T	period under consideration

Demand-driven expenditure

The demand-related expenditure AN_v includes the costs for electricity and gas procurement.

$$AN_v = \sum_{x=1}^x A_{vx} \cdot a \cdot b_{vx}$$

AN_v	Annuity of demand-driven expenditure
A_{vx}	Annuity of consumption costs x
b_{vx}	Price dynamic present value factor for demand-related costs
a	Annuity factor

Different annual price changes are assumed for some cost components. These are shown in the following table and are taken into account in the economic analysis by multiplying the annual costs of the first year by the pricisdynamic present value factor and the annuity factor.

$$b_x = \frac{1 - \left(\frac{r_x}{q}\right)^T}{q - r_x}$$

<i>cost item</i>	<i>Annual gradient</i>
<i>NNE</i>	0,70 %
<i>EEG-levy</i>	-2,14 %
<i>CO₂ trading</i>	5,41 %
<i>natural gas price</i>	0,67 %

Assumptions of annual cost increases

Operating expenditure

In the case of operating expenditure, the technology-specific performance and work-related standard values are used instead of the investment-related factors for maintenance and repair (according to the VDI guideline).

$$AN_O = \left(K_{O\&M_{fix}} \cdot P + K_{O\&M_{var}} \cdot E \right) \cdot b_B \cdot a$$

AN_O Annuity of operating costs

A_0 initial investment amount in €

$K_{O\&M_{fix}}$ Performance-related fixed cost portion of the maintenance costs in €/MW

$K_{O\&M_{var}}$ Work-related share of maintenance costs in €/MWh

P Output of the plant

E Work used by the plant

b_B Price dynamic present value factor

a annuity factor

Revenues

As in the case of electricity costs, no increase or decrease in future revenue from electricity sales is assumed.

$$AN_R = R \cdot b_R \cdot a$$

AN_R Annuity of revenues

R revenues

b_R Price dynamic net present value factor of revenues

a annuity factor

6.2 Plant specific production and storage costs

Another important plant-specific valuation parameter is the output-related prime cost, which is used to calculate the specific costs per output unit generated. The total annuity AN_i calculated previously is compared with the generated annual output $_{tP}(\text{out}_i)$ (t). This allows the heat production costs of PtH plants, the gas production costs of PtG plants and the storage costs of batteries to be mapped.

$$PC_i = \frac{AN_i}{\sum_t P_{th_{out_i}}(t)}$$

District heating network-specific levelized costs of heat

As the integration of further plants such as PtH displaces the heat generation of existing plants, this results in a low number of full-usage hours and thus higher plant-specific WGK of existing plants. In the next step, the economic effects of the use of flexibility options on the total heat production costs of the heating network will be investigated. The heat production costs of the FW network WGK_Netz are calculated by dividing the sum of the total annuity of the individual plants AN_i by the sum of the amount of heat fed into the heat network $P_{th_{out_i}}(t)$. Since the batteries and PtG systems also have an indirect influence on the WGK of the FW networks through coupling with the heat generators, the total annuities of these systems are also taken into account in the calculation of the WGK. The WGK of the grid refer to the heat share provided by gas-fired CHP, peak load heating plants and flexibility options. The renewable plants in the FW grid Prenzlau (component: CHP EE Prenzlau) as well as the external heat generation of the PCK refinery in Schwedt (component: CHP external Schwedt) are not substituted in the model and therefore have no influence on the use of the Flex options. Therefore, an economic analysis of these plants is not carried out.

$$LCOH_{Grid} = \frac{\sum_i AN_i}{\sum_i \sum_t P_{th_{out_i}}(t)}$$

6.3 CO2 emissions

The CO2 emission of the respective energetic outputs of the individual plants within the FW networks is calculated on the basis of the energy sources used in conjunction with their CO2 emission factors. Possible energy source inputs in the system under consideration are natural gas and electricity. While a constant CO2 emission factor is assumed for natural gas, the CO2 intensity of electricity differs with regard to the differentiation between grid electricity and FlexStrom mentioned above. For the purchase of grid electricity, CO2 emissions in the amount of the average assumed electricity mix in Germany are incurred depending on the respective year. The temporary and quantitative FlexStrom determined by the grid and market situation is assumed to be CO2 neutral. If a battery is implemented in the scenario, the Flex options also have the option of obtaining electricity from the battery. The battery itself can draw both FlexStrom and net current and sell also current in the net to Day-ahead market prices, with which the possibility exists that FlexStrom can leave the system borders of the FW nets. Therefore the CO2 emission, which accumulates with the current storage, is calculated balance-fairly from the difference between the annual net purchase and net feed in by multiplying this with the CO2-Emissionsfaktor of the current mixes. As soon as more electricity is fed into the grid from the battery than is drawn from the grid, the CO2 emissions are therefore negative. This consideration is based on the assumption that in this case the battery makes CO2-neutral FlexStrom usable in the general electricity grid, which saves conventional power plant generation and thus reduces the CO2 emission factor of the grid electricity. If more electricity is drawn from the grid than is fed out, the total emissions of the battery are correspondingly positive.

$$CO_{2,Batt} = EF_{el_{Netz}} \cdot (W_{el_{Netz,in}} - W_{el_{Netz,out}})$$

$$spez. CO_{2,Batt,el} = \frac{CO_{2,batt,el}}{W_{el_{out}}}$$

The CO₂ emissions of PtH and PtG result from the respective mains power supplies and those provided by the battery.

$$CO_{2,pth} = EF_{elNetz} \cdot W_{elNetz,in} + spez.CO_{2,Batt,el} \cdot W_{batt_{el},in}$$

$$CO_{2,ptg} = EF_{elNetz} \cdot W_{elNetz,in} + spez.CO_{2,Batt,el} \cdot W_{batt_{el},in}$$

$$spez.CO_{2,ptg} = \frac{CO_{2,ptg}}{W_{gas_{out}}}$$

When calculating the CO₂ emissions of a CHP unit, several methods can be applied⁴. In order to emphasize the advantages over uncoupled heat generation, the so-called efficiency method is applied according to the following formulas:

$$A_{gas} = \frac{\eta_{el}}{\eta_{el} + \eta_{th}}$$

$$CO_{2,chp,th} = A_{gas}(EF_{gas_{grid}} \cdot W_{gas_{grid}} + spez.CO_{2,ptg} \cdot W_{ptg,in})$$

The CO₂ emissions of the heating plant result from the natural gas supply of the network and the supply of synthetic natural gas from the PtG plants with the respective emission factors.

$$CO_{2,hp} = EF_{gas_{grid}} \cdot W_{gas_{grid},in} + spez.CO_{2,ptg} \cdot W_{ptg,in}$$

The total CO₂ emissions of the respective FW network result from the sum of the absolute CO₂ emissions of the individual plants. The CO₂ emissions of the battery are indirectly contained in PtH and PtG via their battery power supplies.

$$CO_{2,DH} = CO_{2,hp} + CO_{2,chp} + CO_{2,pth} + CO_{2,ptg}$$

⁴ MAUCH, CORRADINI, WIESEMAYER & SCHWENTZEK 2010, S. 12

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8.1 windnode_kwum

8.1.1 windnode_kwum package

Subpackages

windnode_kwum.analyses package

Submodules

windnode_kwum.analyses.basics module

Module contents

windnode_kwum.models package

Submodules

windnode_kwum.models.basic_model module

Module contents

windnode_kwum.scenarios package

Submodules

`windnode_kwum.scenarios.basic_scenario` module

`windnode_kwum.scenarios.reference_scenario` module

`windnode_kwum.scenarios.reference_scenario_curtailment` module

Module contents

`windnode_kwum.tools` package

Submodules

`windnode_kwum.tools.config` module

This module provides a highlevel layer for reading and writing config files. There must be a file called “config.ini” in the root-folder of the project. The file has to be of the following structure to be imported correctly.

The filestructure is like:

```
[SectionName] Option1 = value1 Option2 = value2
```

```
windnode_kwum.tools.config.create_data_dirtree()  
    Create data root path, if necessary
```

```
windnode_kwum.tools.config.get(section, key)  
    returns the value of a given key of a given section of the main config file. :param section: the section. :type  
    section: str. :param key: the key. :type key: str. :returns: the value which will be casted to float, int or boolean.  
    if no cast is successfull, the raw string will be returned.
```

```
windnode_kwum.tools.config.get_data_root_dir()  
    Get root dir of data which is located in parent directory of package directory
```

```
windnode_kwum.tools.config.load_config(filename)
```

`windnode_kwum.tools.data` module

`windnode_kwum.tools.draw` module

`windnode_kwum.tools.geo` module

`windnode_kwum.tools.logger` module

```
windnode_kwum.tools.logger.setup_logger(log_dir=None, loglevel=10)  
    Instantiate logger
```

Parameters

- **log_dir** (*str*) – Directory to save log, default: <package_dir>/../logs/
- **loglevel** – Loglevel

Returns

Return type instance of logger

Module contents

Module contents

8.2 setup module

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- `modindex`
- `search`

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