GESTCO final report

Work Package 2, Study area F: Storage in deep coal beds : Germany

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1 Principle

The differences in absorption behaviour of CO_2 and CH_4 can be used for CO_2-storage with simultaneous production of mine gas from coal seams that are not considered for mining any more under actual technical or economical conditions: enhanced coal bed methane production (ECBM), (Stevens and Spector 1998). One ton of coal can adsorb about 30 - 35 m^3 of CO_2 at pressures in excess of 5 to 8 MPa (Cook et al. 2000). One molecule of methane can be exchanged by 1.5 to 5 or 6 molecules of CO_2 depending on the available pressure (van Bergen and Pagnier 2001). CO_2 storage capacities have been calculated using the literature data mentioned above.

2 Estimate of maximal CO_2 storage capacity based on adsorption potential

Coal reserves at depth below of 800 m below surface have been obtained from a database of the Geologischer Dienst NRW (Juch 1994, Daul & Juch 1999), corrected for the volumes of coal produced after 1980. Using an average coal density of 1300 kg/m^3 , and an adsorption capacity of 33 m^3 CO_2 per ton of coal, deep coal seams could adsorb **32 200 – 37 500** Mt of CO_2. Restriction of CO_2 storage to areas without previous mining activity could be a requirement of storage safety. These areas still would offer capacity for storage of about 27 800 Mt of CO_2. Coal reserves at shallower depth are not included in this calculation but they would not significantly alter the results (Annex I).

3 Estimate of CO_2 storage capacity based on exchange potential

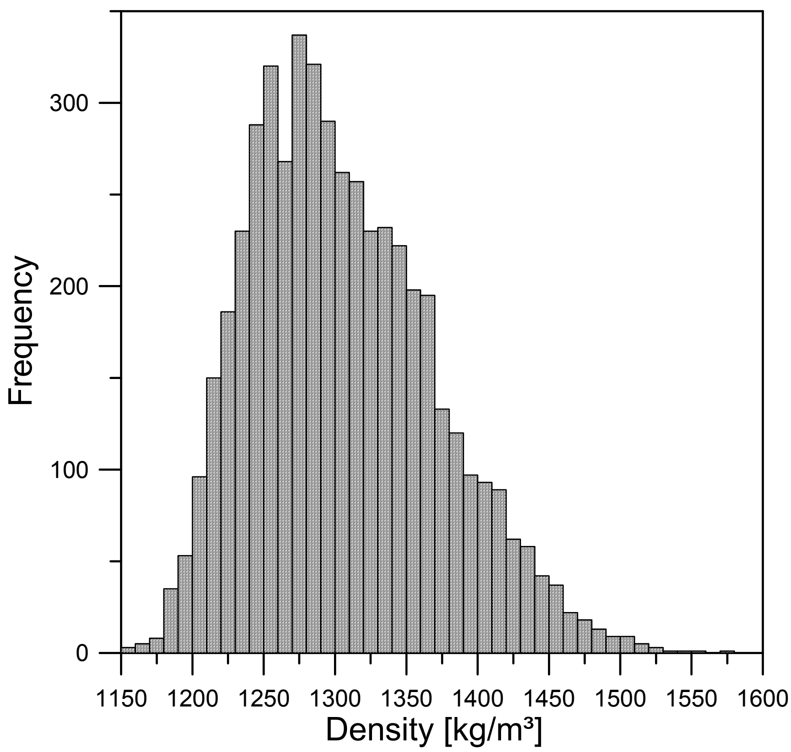
The calculation of storage capacities is associated with different sources of errors. Known or estimated errors have been included in the capacity calculations. The method of Monte Carlo simulations has been used in order to estimate the uncertainties of the calculated storage capacities resulting from these errors.

3.1 Input data

The calculation of coal volumes for tectonic blocs based on mining exposures and wells (Juch 1994) is one source of error. The uncertainty in the depth range of active mining (up to about 1200 m below ground) is assumed to be 3 % relative standard deviation. It is assumed that between 1200 and 2000 m coal exploration wells provide a base for a relatively good volume calculation with an error of 6% and that the error for the deeper coal beds (2000 to

5000 m) is 12 % because deep wells are scarce. Sequestration at these depths is unlikely, as permeability decreases and investment costs increase accordingly.

The coal volumes are given for depth ranges, mostly of 100 m, partially also 200 m intervals. The error range of the actual depth of coal seams thus is ± 50 or 100 m, with respect to the mean depth of the intervals. The conversion of coal volume to coal mass has not taken into account compositional differences between different coal types. An average coal density of 1300 kg/m^3 has been used. Simulated coal densities range from 1150 to 1570 kg/m^3.

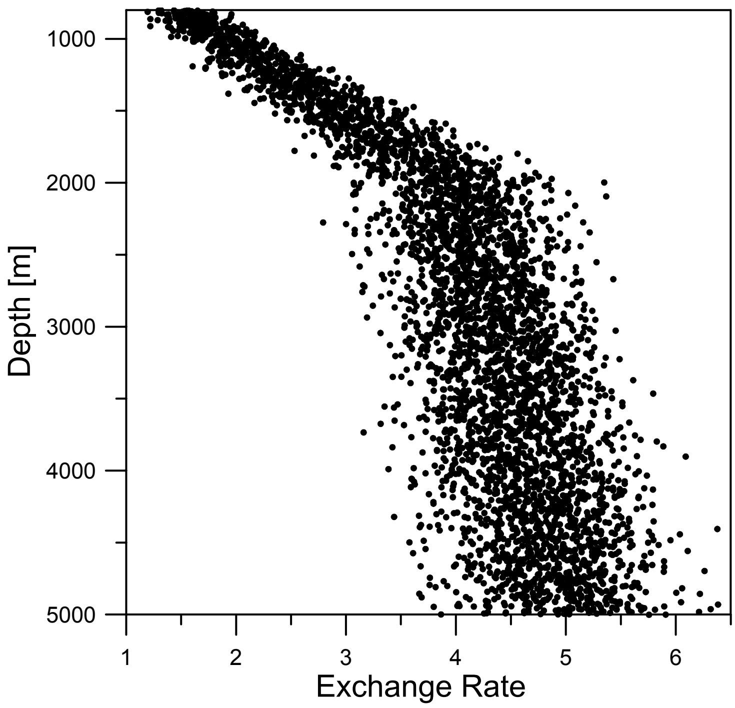


Simulated distribution of coal densities.

Methane gas contents of German coal have been measured by Gaschnitz (2001). An overall average value of 5 m^3/t has been assumed for deep coal seams from the Ruhr area, Erkelenz and Ibbenbüren. Coal from the well Weiher1 in the Saar area contains about 8 m^3/t (Gaschnitz et al. 2000). A normal distribution with a standard deviation of 0.75 m^3/t covers the observed range of gas concentration for individual wells. The concentrations of minor constituents in the gas phase, has been neglected.

Average exchange capacities CO_2/CH_4 are assumed to be depth dependant (pressure effect) and increase linearly from 1.5 to 4 in 800 to 2000 m depth and from 4 to 5 in 2000 to 5000 m depth. A relative standard deviation of 10 % has been assumed for the exchange capacity.

Additional uncertainty due to undersaturation of most coals is not considered, as this would negatively influence CH_4 production only, not CO_2 storage.

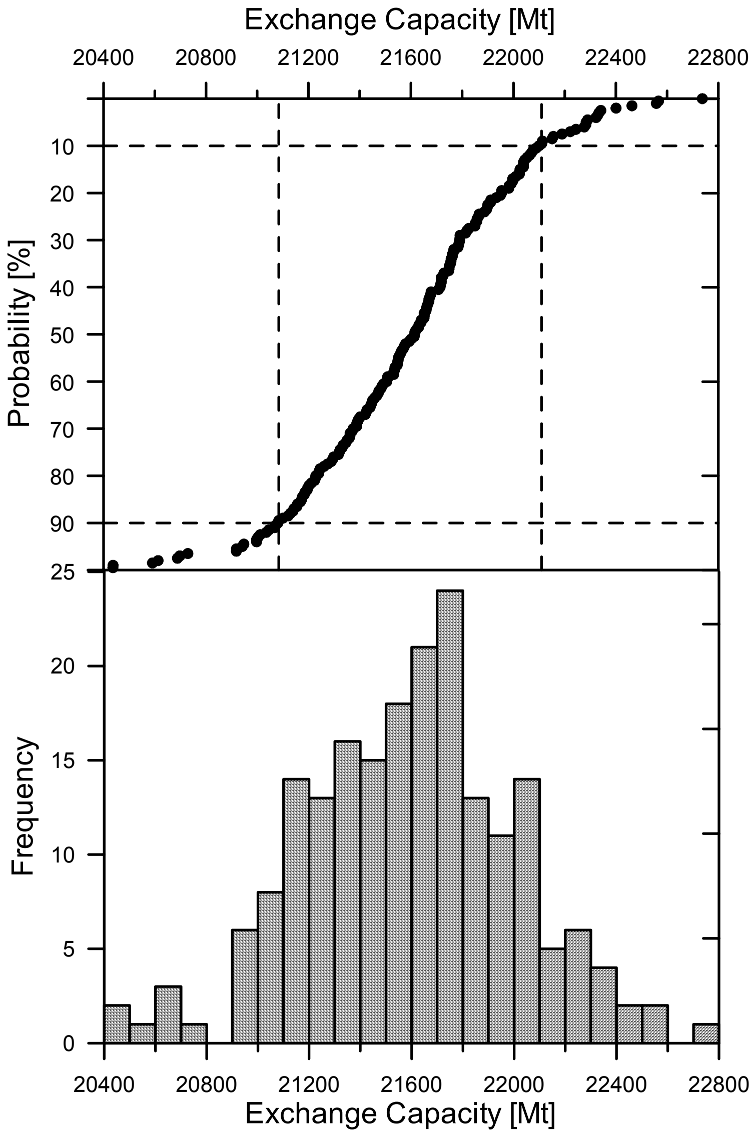


Simulated distribution of molecular gas exchange rates

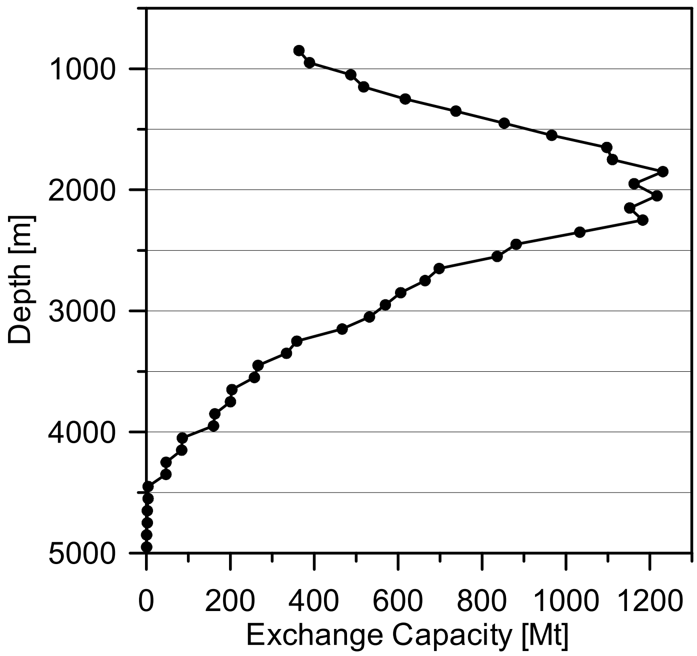
3.2 Volumetric Exchange capacity

Monte-Carlo simulations taking into account the uncertainties of the input data described in the proceeding chapter are used to calculate exchange capacities. Assuming average gas contents of 8 and 5 m^3 per ton of coal for deep coal seams in the Saar area and the other German coal mining districts respectively, the CO_2 exchange capacity of coal beds for CO_2 is about 21 600 ± 415 Mt. That is about two thirds of the adsorption capacity, which assumes gas saturation of the coal. The calculation of exchange capacity includes the actual gas content of the coal, that is more or less undersaturated.

The numerical simulations suggest, that known and estimated statistical errors have little effect on the overall storage capacity. The relative standard deviation of the sum of the simulated values for all fields is 1.9 % only. However, that is true only for the total sum of the exchange capacities, where averaging over 552 partial volumes has reduced the error. The relative standard deviation of the exchange capacities simulated for individual depth intervals and mining areas is about 20 %. The mean exchange capacity of the areas not affected by mining is 17 300 Mt CO_2.



Distribution of simulated volumetric exchange capacities for CO_2 in deep coal beds in Germany.



CO_2 exchange capacity in 100 m depth intervals.

The vertical distribution of exchange capacities indicates a maximum between about 1500 and 2500 m depth. However, CO_2 may also be sequestered at pore spaces not occupied by CH_4, due to undersaturation.

3.3 Estimate of practical exchange capacities

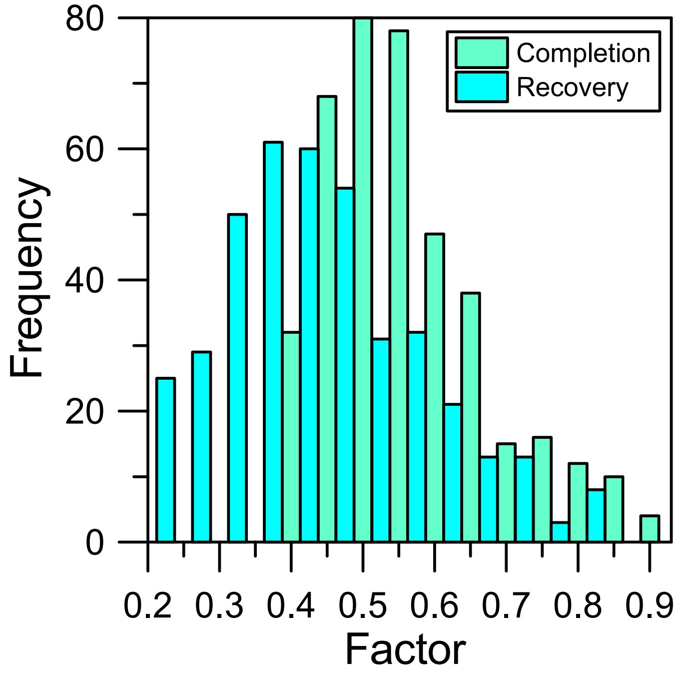
There are errors of unknown size in addition to those included in the simulations described above:

- Completion factor (van Bergen and Pagnier 2001). The storage capacity values have been calculated for the complete sequence of known coal seams in each area, typically about 2000 m or more. The completion factor is an estimate of the net cumulative coal thickness within a well, that will participate in gas exchange. Completion factors of 0.4 to 0.9 are used by van Bergen and Pagnier (2001).
- Recovery factor The recovery factor indicates the fraction of the adsorbed methane that can be produced from the coal seams. While conventional coal bed methane production recovers about 20 to 60 % of the stored gas, the simultaneous injection of CO_2 can enhance the recovery factor for CH_4 to 80 % or more (Stevens and Pekot 1999).
- Free CO_2 phase. In addition to adsorption, the injection of CO_2 under pressure could frac the coal and a supercritical phase spreading out in the seam could occupy fractures and joints in the coal and adjacent rocks.

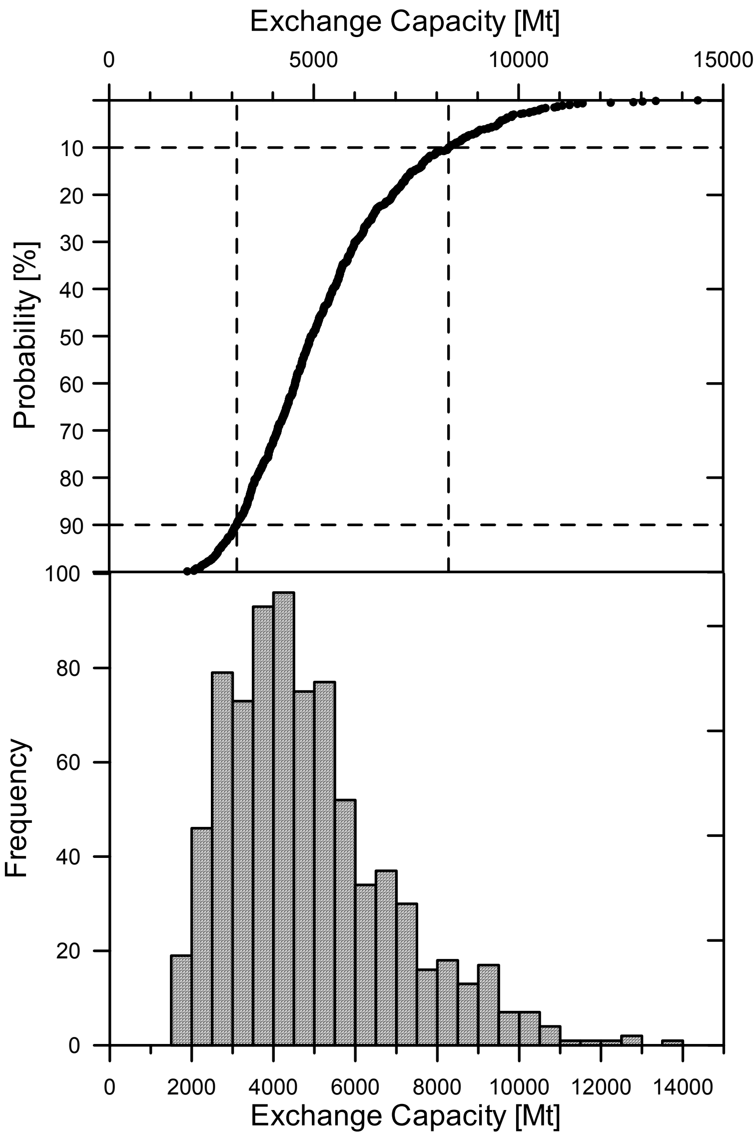
These effects depend on the production/injection technology and strategy. Thus, they have not been included in the exchange capacity simulation. They have to be considered however in any realistic (economic) assessment of storage capacities in coal beds.

Triangular distributions of completion and recovery factors have been simulated according to the values van Bergen and Pagnier (2001) have used. The average product of completion times recovery factors is 0.25 ± 0.1. Using these factor distributions the adsorption exchange capacities would reduce to values in a likely range of 3100 to 8300 Mt CO_2, with a mean value of 5400 Mt CO_2.

	Minimum	most likely	Maximum
Completion Factor	0.4	0.5	0.9
Recovery Factor	0.2	0.4	0.85



Simulated completion and recovery factor distribution used to calculate technical exchange capacities.



Distribution of simulated exchange capacities for CO_2 in deep coal beds in Germany under consideration of likely geotechnical conditions.

Restriction to areas without mining activity (until 1980) leaves 4325 Mt of storage capacity (median exchange and recovery factors provided). The calculated values are within the range of values calculated for other coal basins world-wide 3.8 to 150 Gt (Stevens et al. 1998).

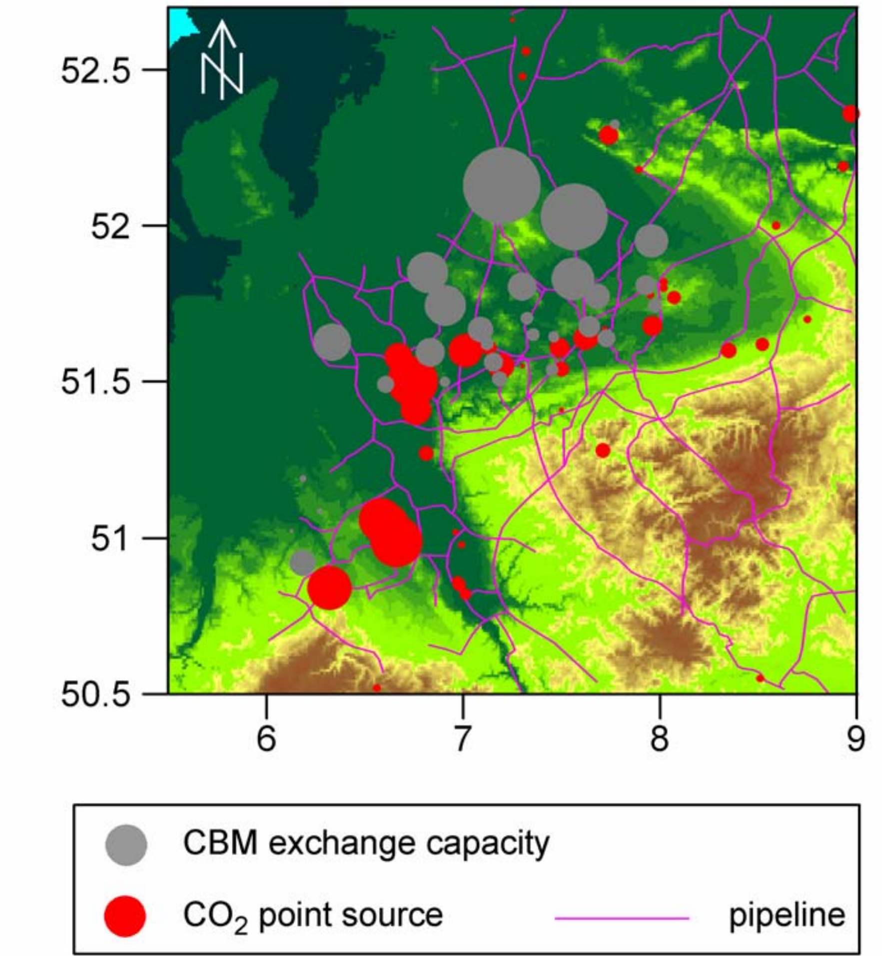
Since the permeability of deep coal seams is very low, van Bergen considers only coal to a depth of up to 1.5 km suitable for CO_2 injection. The exchange capacity for the mapped German coal seams between 800 and 1500 m depth would be only 622 to 1670 Mt (90 to 10 % probability range). Coal seams are presently mined in this depth range. Restricting the calculated exchange values to areas without previous mining a range of 371 to 1670 Mt, with a median of 585 Mt is likely.

4 Discussion

The exchange capacities are not normally distributed. Completion and recovery factors strongly depend on geotechnical factors. Technical improvements of the still young practice of ECBM production are likely. Thus a shift of recovery and completion factors towards higher values is likely, consequently leading to higher overall storage capacities for CO_2. Free space storage, dissolution and penetration of CO_2 into the rocks surrounding coal seams will probably increase the storage capacities also. The values provided are therefore to be regarded as minimum values.

A major unresolved issue is the large number of deep wells and pipeline connections required to cover the large area of the deep seams. Thus the economical potential for CO_2 storage is probably much lower than the technical potential. On the other hand, coal seams are well located with respect to industrial point sources of CO_2.

North of the Ruhr industrial basin, deep coal seams of the Münsterländer Becken provide storage capacity in close vicinity to major point sources: coal fired power plants, integrated blast furnace iron and steel works. Further to the Southwest lignite fired power plants in the Niederrheinische Bucht form additional important sources. An existing network of major pipelines could provide corridors for pipeline transport in the densely populated and industrialised region. The Saarland is another industrial area with major storage capacity for CO_2 in deep coal beds.



CO_2/CH_4 exchange capacity of deep coal seams in the Ruhr area.

Carboniferous coal seams extend further north beyond the Ibbenbüren mining area. At greater depths below the southern Rotliegend of the southern Permian Basin. These coal seams have not been mapped and are not included in the data base of Juch (1994). The have not been included in the storage capacity calculations because injection into such deep seams is probably economically not feasible and less deep storage options in gas fields or aquifers overlying the carboniferous strata would be favoured.

In general it can be stated that the storage capacity of deep coal beds can only be estimated with great uncertainty at present. The assessment of more realistic storage capacities will depend very much on technological developments and on further research about the physicochemical properties of local coals under in-situ conditions.

5 References

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6 Annex I

Volumetric storage capacities in abandoned coal mines (void volume) and coal seams

(adsorption vs. exchange capacity; completion and recovery factors not included)

district	field (Juch 1994)	void storage capacity [Mt]	adsorption capacity [Mt]	exchange capacity [Mt]
Ruhr	1.1	48,64	157,00	64,01
	1.2	288,79	371,62	145,63
	1.3	114,19	246,66	83,00
	2.1	3,52	273,38	98,97
	2.2	15,82	127,22	46,20
	2.3	0,00	546,22	227,91
	2.4	0,00	435,52	193,90
	3.1	8,93	113,88	39,46
	3.2	98,94	386,50	166,75
	3.3	36,83	177,30	66,50
	3.4	0,00	675,15	328,93
	4.1	5,29	178,62	68,36
	4.2	1,71	153,75	62,25
	4.3	0,00	1776,99	1024,32
	4.4	0,00	1081,97	604,69
	5.1	1,51	338,36	129,46
	5.2	103,72	1017,61	437,84
	5.3	44,01	717,09	326,27
	5.4	0,00	851,06	420,36
Münsterland	6.1	0,00	1569,97	777,73
	6.2	0,00	1831,47	934,28
	6.3	0,00	1721,29	949,11
	6.4	0,00	4439,09	2704,16
	6.5	0,00	5833,24	3622,10
Ibbenbüren	6.6	1,45	93,43	33,96
Aachen/ Erkelenz	7.1	0,00	1187,26	351,78
	7.2	0,00	14,57	7,07
	7.3	0,34	37,68	10,42
	7.4	0,00	39,72	13,16
Saar-Nahe	8.1	2,11	991,40	737,99
	8.2	0,00	2439,76	1863,93
	8.3	1,75	686,19	676,61
	8.4	1,75	1530,89	1104,15
	8.5	0,00	2087,11	2001,93
	8.6	0,00	1246,93	1274,74