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RESIDUAL SPACE VOLUMES IN ABANDONED COAL MINES OF THE BELGIAN CAMPINE BASIN AND POSSIBILITIES FOR USE

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(9 figures)

ABSTRACT. The abandoned former coal mines of the Campine basin represent significant, human induced subsurface reservoirs. They consist of two interconnected main parts: the large, mined-out areas of former coal production (panels and most galleries) and the principal infrastructure of stone drifts, shafts, bunker and platform areas.

Both main elements have their own flow characteristics due to general differences in porosity and permeability (poro / perm) conditions. The former infrastructure is assumed to have remained largely open. Back-filled and goaf areas of the formerly mined panels contain effective porosities in the order of 3 - 8 %. Their permeability changes from a multi-directional 'normal' flow pattern in the centre of the goaf sheet to a more unidirectional, fissure-guided (semi-) perpendicular flow pattern, in the outer, surrounding parts.

For the former collieries in the Campine basin a total remaining volume of over 35 million m^3 has been calculated, roughly situated within the 450 - 1050 m depth interval. Presently these mines are still only partially flooded by rising mine water.

To assess the utility possibilities of these former mines, Flanders has engaged into a GIS-mapping program of both former infrastructure and goaf areas of these mines. This allows selection of optimal areas for energy production, like abandoned coal mine methane (ACMM) and / or (enhanced) coalbed methane (ECBM). Geothermal use of, or energy storage in the mine water is feasible as well.

Storage of industrial residues, natural gas (methane; CH_4) and in some cases even (of limited amounts) of carbon dioxide (CO_2) appears feasible too. If (well) prepared before abandonment, the former mines may even be used for production of electricity (water flow in micro-turbines) or geothermal energy (CO_2 convection systems).

Keywords: Campine basin, coal mines, porosity, permeability, methane, energy storage.

1. General background

The Belgian Campine basin (fig. 1) is a concealed part of the large, paralic Carboniferous coal basin of northwest Europe. It is situated north of the subcropping Cambrian - Silurian basement rocks of the London-Brabant Massif of central Belgium. At this actual southern edge of the basin, clastic Middle to Late Devonian strata (Givetian - Famennian) subcrop against this Caledonian deformed basement. To the north these rocks are overlain by Lower Carboniferous carbonates (Dinantian; Tournaisian and Visean) followed by clastic Upper Carboniferous sediments of the Silesian (Namurian to Westphalian D).

In the northeastern part of the basin, these successive Carboniferous strata are disconformably covered by an onlapping wedge of Permian to Jurassic sediments. In turn, both this northeastern, predominant Mesozoic succession, as well as the Palaeozoic sediments in the other parts of the basin, are disconformably overlain by younger, Upper Cretaceous and Cenozoic deposits. Eastward the basin continues into the Carboniferous coalfields of south-Limburg in the Netherlands. To the north / northeast it is bounded by the Roer Valley graben.

Structurally, the Carboniferous of the Campine basin is subdivided by the N-S striking Donderslag fault system into two sub-basins, each of which shows a different sedimentological and burial history.

The shallower parts of the Campine basin have been extensively mined for coal in the previous century (fig. 1). For each colliery this has resulted in an extensive, residual subsurface network of highly permeable semi-horizontal corridors (conduits), connected by other vertical corridors and (often) inclined, more irregular porous zones of lesser permeability. These abandoned mine-workings therefore, are considered as human induced, artificial reservoirs.

After the final closure of the collieries during the early nineties, the pumping of mine water stopped and a gradual rise of water into the former workings started. However - as no monitoring conduits have been installed - the rate of this strongly pressure related rise is not really known. In the Dutch part of the basin (less overburden) this rate was established to diminish gradually from over 25 m / year to less than 4 m / year during the last stages of flooding (Van Tongeren, 2002; Van Rooijen, 2000). After a flooding period of 30 to 35 years, the Dutch Mines therefore - with maximum mining depths between 700

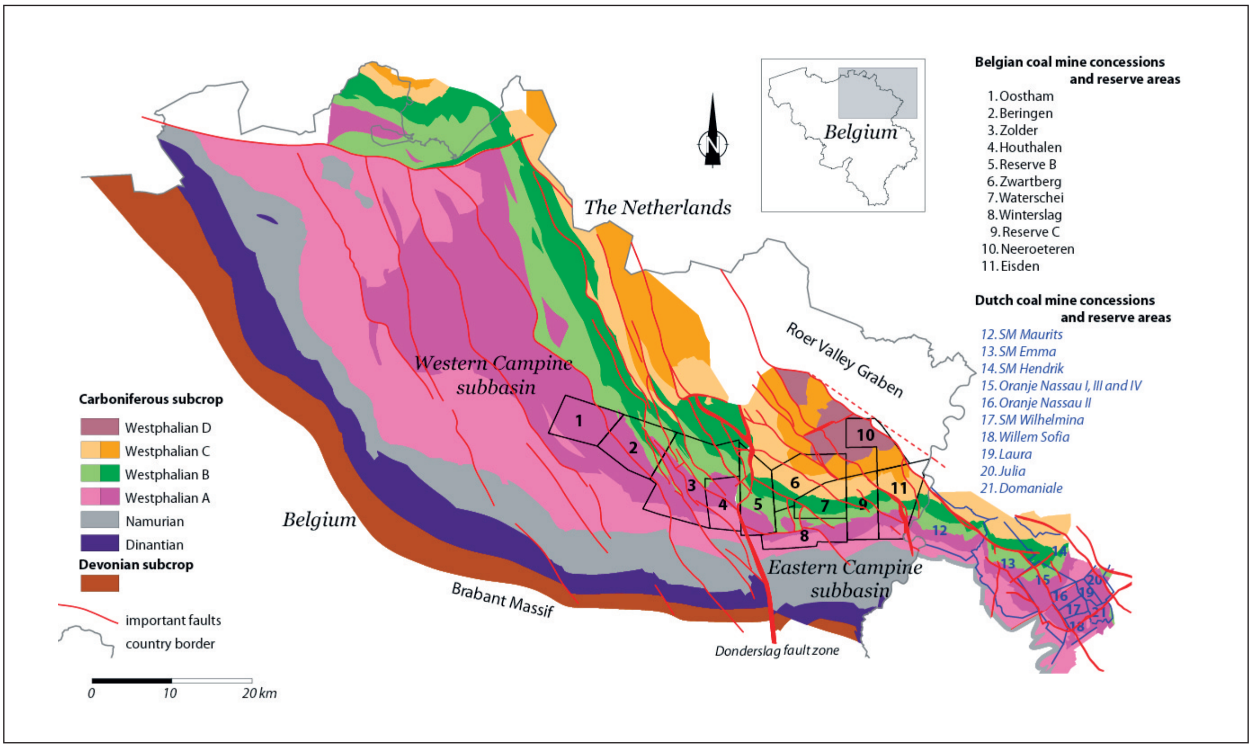

Figure 1 The Campine basin. Subcrop map of Devonian and Carboniferous rocks with important faults and concession-bounderies of former Belgian and Dutch collieries.

and 1100 m - are now virtually completely refilled with formation and infiltration water.

The above warrants the assumption that most mines in the Belgian part of the Campine basin are only partially water-filled at present! They are likely to be still dry in their upper halves. This consequently means that these reservoirs may actually (still) be used for either gas production (abandoned coal mine methane [ACMM] and [enhanced] coalbed methane [E]CBM), geothermal scenarios and / or energy or CO_2- storage applications.

b) The remaining open vertical spaces and porosity of the main- and airshafts, their surrounding loading- and storage platforms and the vertical (coal) transport connections between the different mining levels (rising stone drifts; blind-shafts). At colliery closure, the production / aeration shafts generally have been filled from surface up till the depth of the first mine level. The majority of these vertical infrastructural works are unlikely to have collapsed. They generally provide good conduits with very good and rather uniform poro / perm conditions.

2. Principal elements of the subsurface mine-reservoirs

These mine-reservoirs predominantly consist of the following elements (fig. 2):

a) The extensive system of semi-horizontal stone drifts, major railways (figs 3a, b) and main galleries (the former transportation infrastructure of the mine). Especially once flooded, much of this infrastructure has probably remained open and uncollapsed (incompressibility of water). In this way, the system forms tunnel-shaped conduits with excellent poro / perm conditions. Even in collapsed and / or strongly deformed parts, poro / perm conditions still will be relatively large in general, and also quite homogeneous. At some locations dams may be present in these corridors. However, they are not considered to be gas / water tight in the long run.

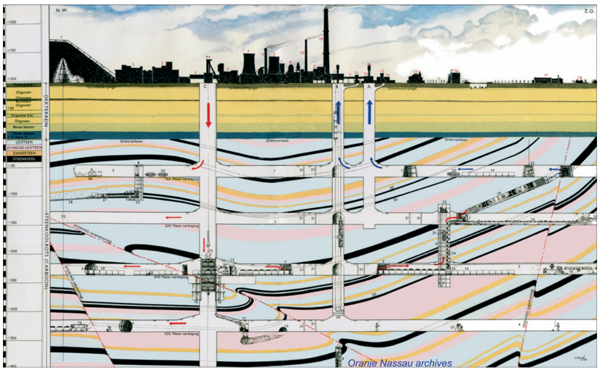

Figure 2. Schematic section of a coal mine. The main shafts, stone drifts, blind shafts and mined coal seams are integrated parts of the human induced, subsurface reservoir (yellow: overburden rocks; black: coal seams).

Figure 3a. Supporting the end of a main stone drift (inclined panel support in background).

Figure 3b. Railway corridors in the Beringen coal mine.

c) The remaining cavities, vugs and porosities of both the collapsed and / or back-filled (figs. 4a, b) coal mining panels (goaf areas) and their accessory, surrounding roads. All combined, these former production panels usually occupy rather extensive, inclined and undulating surfaces, generally possessing much lower and far more heterogeneous poro / perm conditions than the former old infrastructure. Their remaining poro / perm conditions are both largely a function of the surrounding rock types as the mining methods used.

d) The broken and sheared parts of the surrounding rocks of these goaf areas. Here, mining conditions, rock type and rock positions (depth, dip, bedding, banding, mineralogy, etc.) dominate the remaining poro / perm conditions even more. Generally, a sort of layered zonation of fissure-intensities has developed, (semi) perpendicular to the dip of the mined coal seams. Away from the mined seams the fissuring decreases in a non-linear way. The intensity of induced joints (diameter and amount / m^2) and related poro / perm conditions decreases likewise. The features of c and d are strongly related and grade into each other. Their poro / perm values are also considerably less than those of the stone drifts and (blind)shafts, due to the large, compressive (overburden) forces.

Figure 4a. First generation back-filled pillar, still supported by wood; former Eisden colliery (Belgium, Eastern Campine basin).

Figure 4b. Hydraulically stowed pillar.

The original, intrinsic porosities of remaining coals and surrounding sterile rocks is generally very low. Only in sandstone beds a locally important fissure porosity may be present. In practice therefore, the intrinsic poro / perm characteristics of the Carboniferous rocks in the Campine basin are usually neglected in regard to the other elements. At certain specific applications however - e.g. at sorption effects, or at places in / near (induced) jointing of (thicker) sandstones - this intrinsic porosity should yet be taken into consideration.

3. Estimates of residual volume

Recent German investigations in the Ruhr basin have shown a remaining porosity range of 5 to 10 % for collapsed panel areas (the German 'Bergschadenkunde'; Kunz, 2000) and collapsed accessory panel-roads (= most galleries). Although their figures did not include back-filled areas, these investigations also showed that back-filled panels have a larger porosity than the surrounding, unmined rocks. They remain porous pathways. Also the filling material of most surface shafts is more permeable than the original surrounding rocks.

At places in the Ruhr area, the mining and its inherent subsidence have created (gas-)permeability channels from the mined Carboniferous rock parts into the overburden. Locally, accumulating mine-gas in these strata even slowly migrated towards the surface through poorly filled shafts! A similar case has been reported from the former Borinage mining district in Belgium (M. Dusar, Belgian Geological Survey, pers. comm.). These phenomena have not been reported however, from the Campine basin. In the Belgian part of this basin the overburden is relatively thick (ca. 200 - 600 m) and contains various aquifers in both its Mesozoic and Cenozoic strata.

The German investigations further confirm that stone drifts collapse (very) incompletely. Most of these drifts remain good, open conducts until long after colliery closure**.** The study concluded that each former colliery is likely to still have a residual average, total porosity volume of several million m^3 (Kunz, 2000).

Studies of Labasse (1965) give a remaining volume percentage of around 5 % for back-filled areas in Belgium. In the southern Belgian coal basins however, residual volumes of even 20 % are mentioned (unpublished study of underground gas-storage by Distrigas) and also in the Nord / Pas-de-Calais basin (France) an average rest porosity of 18 % has been accepted in former studies.

Figures for Silesian coal mines (Malolepszy & Ostaficzuk, 1999) give a high estimate of the remaining pore / joint porosity of 20 % as well. In this region about 50 % of the production panels is even stated to have been back-filled!

Apart from varying research methodologies, the differences in residual porosities described above are likely to have been caused by combinations of regional differences in lithology (e.g. shale / silt / sand ratios) burial histories (rate of compaction) and / or mining techniques and intensity.

In regard to the Ruhr area, Berding (1952) found a similar order of magnitude for the remaining, effective porosity in the Netherlands in his study of a sudden water-discharge from an abandoned panel area in the Dutch mine 'Maurits'. This colliery at the Belgian / Dutch border (the Maas river) is located in the extreme western part of the former Dutch mining district and lies opposite the most eastern, former Belgian 'Eisden' colliery (fig. 1). The flow-graph of the out-flowing waters of a separate, previously mined and water-filled panel that was tapped by subsurface drilling was used to measure its remaining porosity and permeability. The panel consisted of a pneumatically back-filled (40 %) and a collapsed part (60 %) and could indeed be considered as a single, individual water reservoir.

The overall, effective porosity of the complete panel appeared 7 %. In this figure, both mining induced, remaining porosities for goaf and pneumatically back-filled areas, as well as the intrinsic rock- and fissure porosities are included. The effective, overall permeability of the panel was rather high with a K-value of 1000 (Berding, 1952).

Considering the general resemblance of the Carboniferous lithology and sedimentological setting between the Belgian Campine, the former Dutch south-Limburg mining district and the German Ruhr area, we consider the German figures of 5 - 10 % (Kunz, 2000) to represent the extreme and limiting figures for the remaining porosity values of goaf areas in the Campine basin. Most effective porosity figures therefore, will likely remain between these limiting values.

Combining the figures of Berding (1952) with the presumption that goaf areas have higher porosities than back-filled areas (figs. 4a,b) we have taken a general effective porosity volume of about 8 % for goaf areas and about 5.5 % for pneumatically back-filled terrains as (most) suitable. The average figure of 5.5 %, applied to the porosity of pneumatically back-filled areas, agrees well with the 5 % figure of Labasse (1965).

The subsidence ratio between pneumatically and hydraulically back-filled areas in the Campine basin is 0.5 : 0.3. Assuming that this difference is predominantly caused by the density differences of the fills only, a general average effective porosity value of about 3.3 % may be attributed to the hydraulically back-filled panels in this basin.

The collapsed panel areas usually form inclined, somewhat undulating sheet-like zones of maximal 35 m of effective width (fluid flow applications) connected to the generally more rectangular framework of stone-drift corridors and blind shafts. Their largest poro / perm values are centered around the position of the formerly

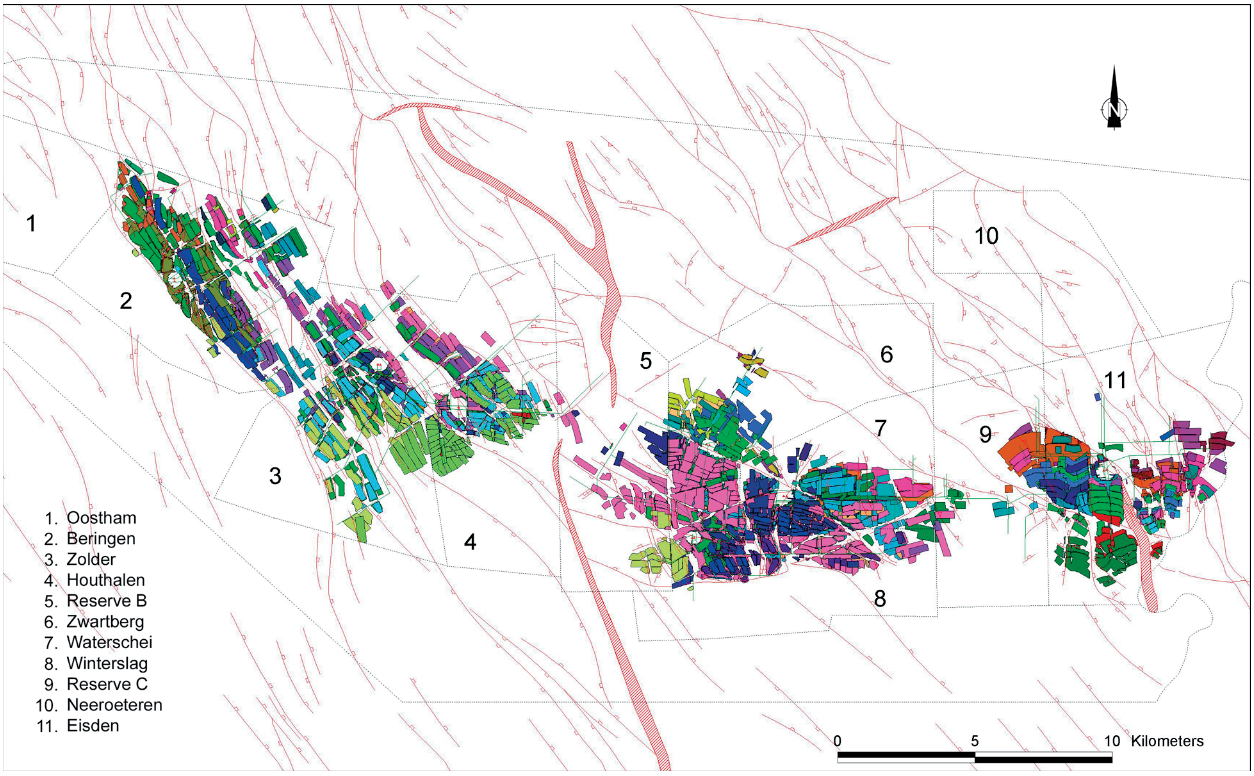

Figure 5. Belgian Campine basin: GIS surface projection of mined panels combined with mapped fault positions. Colours represent different mined coal seams.

mined coal seam and at their edges in contact with unmined rocks (differential roof sagging). The porosity and flow conditions in these central parts gradually change from being relatively uniform, towards more unidirectional and fissure-controlled in the more distal parts. The mining induced rock fissures may indeed extend to about 120 m above, and 60 m below the mined seam (Stuffken, 1957). However, as porosity volumes in these utter ranges are minimal, they can usually be ignored in non-gas flow applications.

As the above porosity figures represent the remaining volumes within the former production panels and the original panel-volume itself is related to the original production volume of coals and dirt, these two figures are strongly related. Therefore, if the general 'mixing ratio' of produced coals and their sterile rock of a mine are established, its gross production figure (of pure coal) can be used to calculate the effective, remaining volume by using the above established figures and adding those volume(s) of the former main infrastructural parts still assumed to be open.

In this way - and only adding 25 % (as a minimal percentage) of the calculated former infrastructural volume assumed to have remained open - a remaining volume of over 5 million m^3 has been calculated for the former Belgian Beringen colliery (figs. 1, 5, 9). If identical mixing ratios and assumptions are applied to all the abandoned Belgian coal mines in the Campine basin, a total subsurface volume of over 35 million m^3 should still be present (Van Tongeren & Dreesen, 2000).

4. Reservoir mapping

To obtain the required parameters and to facilitate potential future applications of these residual volumes, the Flemish Institute for Technological Research (Vito) - commissioned by the Flemish ANRE (*Administration of Natural Resources and Energy; part of the Flemish Ministry of Economic Affairs*) department - has engaged into a mapping program of the combined infrastructure and worked panels of these former collieries. The mapping data are stored into an ArcInfo GIS data-base (Geographical Information System) and finally will be included in the overall subsurface data-base system of Flanders (Databank Ondergrond Vlaanderen; DOV). In this way, it becomes possible to relate e.g. geological and / or surface data to the formerly mined areas (fig. 5).

This is a prerequisite for most studies and applications, especially for the exact positioning of ACMM production facilities, (E)CBM and geothermal production and / or injection drillholes, flow-path' considerations of either internally present CH_4, CO_2 and / or water, and the location of facilities at the surface.

5. Examples and potential use

The energy supply of former coal mines has not necessarily stopped at their closures. Although coal production in many countries has become uneconomic, energy is still in growing demand - even increasingly. The interest therefore, to use former (coal) mines in programs of energy production or storage, is also growing.

Next to the actual gas production from active coal mines, continued gas production from abandoned mines (ACMM) is increasing rapidly in a number of countries; a.o. in the German Ruhr area (e.g. near the cities of Herne and Lünen, fig. 6) and in a number of British areas. Currently ACMM is predominantly used as low quality fuel for electricity generation, but in some cases it appears even pure enough for direct use. In Japan the former Akabira Mine is presently scheduled for gas production and electricity generation (Northwest Fuel Development Inc.2000). Some closed colliery parts have also been used for the injection and storage of industrial wastes (Ruhr area; Klinger, 1994). Geothermal energy production and / or energy storage by use of the water in flooded (coal) mines is another possibility. In the Netherlands, the city of Heerlen is underlain by an extensive flooded area of subsurface infrastructure and collapsed production panels of the former Oranje Nassau collieries (fig. 1; four collieries with total of 10 x 10^6 m^3 of residual volume). The scheduled use of this mine water in general energy provision-schemes for either heat and / or cold storage applications, or more conventional geothermal energy production, appears quite promising (Van Tongeren, 2002; fig. 7). To integrate these energy related mine water capacities into the overall energy-concept of a newly planned quarter of the Heerlen city, an initial GIS-mapping programme, including general volume-, temperature- and water-geochemistry determinations has been carried out for a large part of the O.N.-I colliery (figs. 7, 8). The study has been combined with investigations into the technical / financial feasibility of the mine water use, in various schemes of optimal production / provision of sustainable energy. Especially in combination with other sources of sustainable energy - e.g. wind- or solar energy - the deeper mine water parts appear very useful for heat storage and production. Shallow parts will be used to meet the large demand for cooling and cold storage.

If certain provisions are taken prior to mine abandonment (parts of) the infrastructure may be modified to be suitably used in (limited) electricity production, by intermittent water flow along micro-turbines in (series of) small shafts (Van Tongeren, 2002).

Since 1978 natural gas has been successfully stored under low pressure conditions in, and (re)produced from, abandoned coal mines in the southern Belgian region of Wallonia (Moerman, 1982) by the gas distribution company Distrigas. This occurred in closed, non-flooded mines at the towns Péronnes and Anderlues (actually stopped) near Charleroi. Another gas storage example is the former Leyden coal mine in Colorado, USA.

The non-flooded parts of the former Campine coal mines appear even more suitable to this kind of gas storage. At the times of their original closures (eighties / early nineties) - or when actually pumped dry again - over 500 million m^3 of natural gas might have been stored at low pressures of < 20 bars (Van Tongeren & Dreesen, 2000).

Moreover, in most former mines the large zones of stress release induced by former mining activities should be used to facilitate coalbed methane production (CBM) in avoiding the usual low-porosity problems of the coal beds (fig. 9). Also, various (parts of the) mines may be suitable for the (temporarily) storage and (re-)use of the propelling gases CO_2 and / or N_2 at enhanced CBM production scenarios (ECBM).

In certain mines CO_2 convection currents and related adiabatic processes might even be used in large heat pump scenarios to provide geothermal energy (e.g. the former Beringen colliery in the Campine basin; Piessens & Dusar, 2002).

Figure 6. Abandoned coal mine gas (ACMM) production at Lünen Ruhr area, Germany. Gas (about 60% CH_4) flows from the former shaft towards 3 gas-engine generators for production of electricity (total: 4MW).

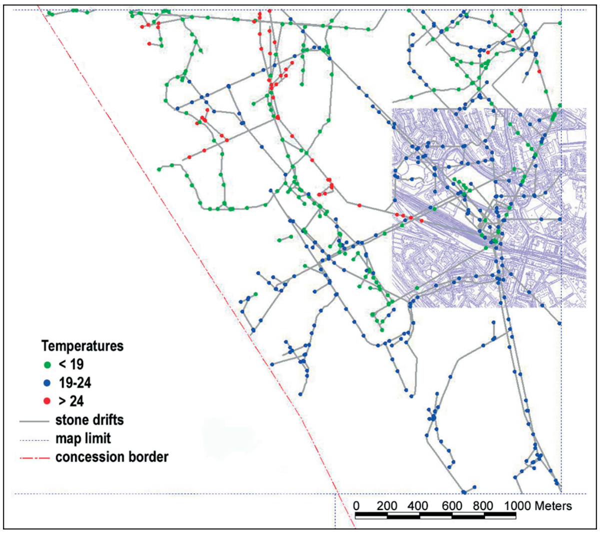

Figure 7. Calculated subsurface temperatures of the stone drifts in a part of the Oranje Nassau I colliery.

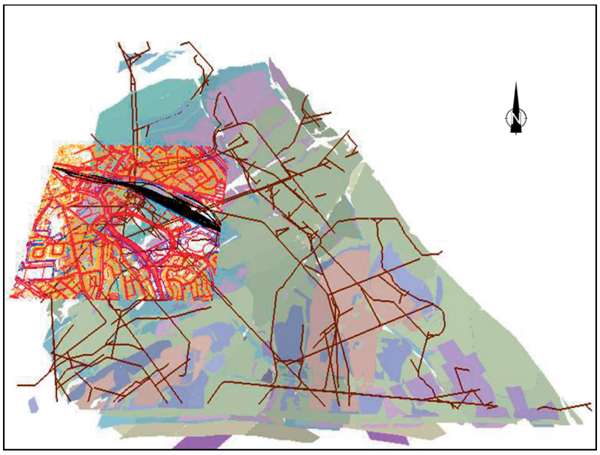

Figure 8. Tilted surface projection of panels and main stone drifts of the Oranje Nassau I colliery and the Heerlen city target area.

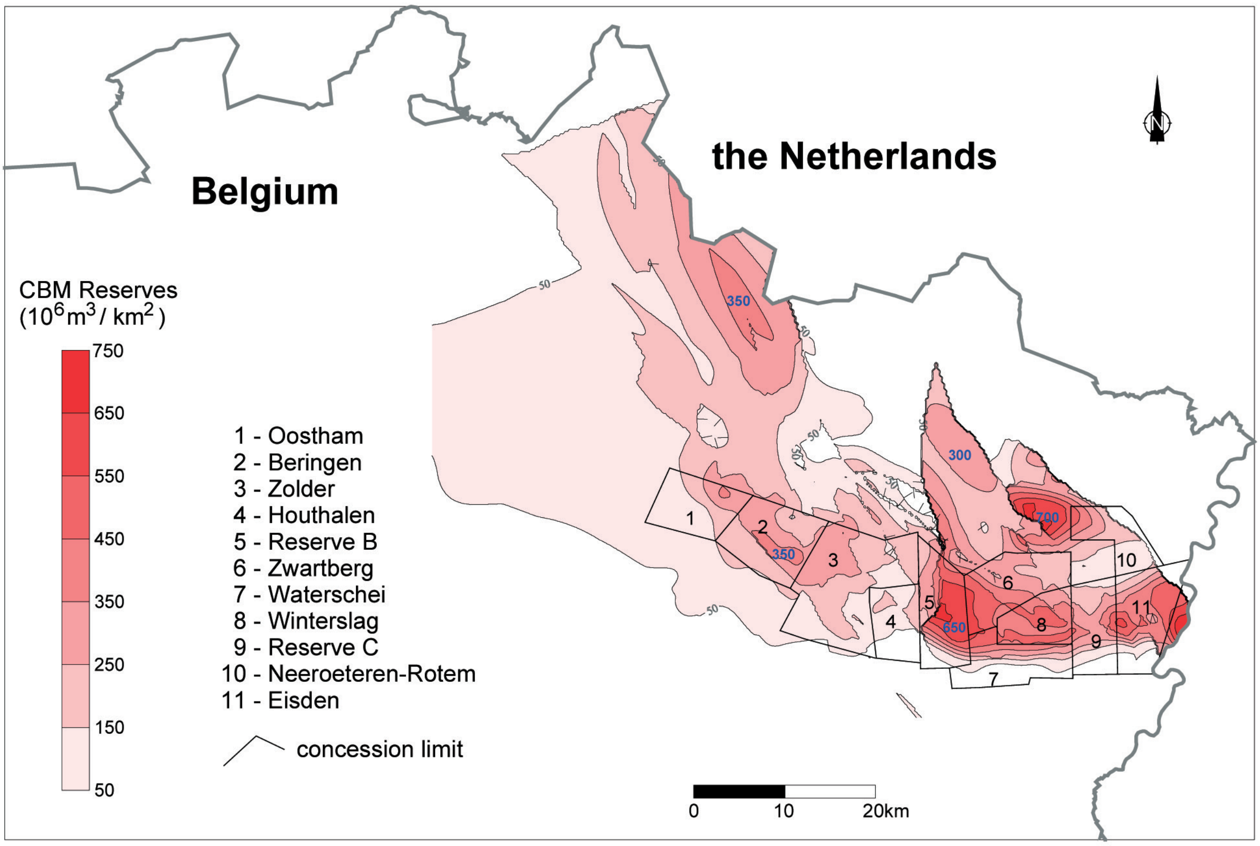

Figure 9. Location of former Belgian coal mining concessions and coalbed methane concentration zones. Highest anomalous values are indicated in blue.

The above summary is a non exhaustive list of actual possibilities that many (abandoned) collieries still may provide. Especially in future energy provision / storage schemes of local energy concepts. We not only believe that many of the above scenarios are well applicable to the former Belgian coal mines in the Campine basin, but also that similar concepts may well be successfully applied in many (former) mining regions in the world.

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