Development of the first deep geothermal doublet in the Campine Basin of Belgium

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In the fall of 2015 the first deep geothermal well was drilled in the municipality of Mol, Belgium. The primary objective was to explore the geothermal reservoir characteristics and the exact depth of the Carboniferous Limestone Group. Based on the test results of exploration well MOL-GT-01, a second well was drilled in spring 2016 creating a geothermal doublet of one vertical well (3,610 m along hole) and one deviated well (4,341 m along hole). Both wells give new stratigraphic and structural insights into the geological history of the Campine Basin. Furthermore, the presence of a geothermal reservoir at depths below 2,500 m has been demonstrated for the first time in Belgium, unlocking opportunities for new developments elsewhere.

A l'automne 2015, le premier puits géothermique profond a été réalisé sur la commune de Mol, en Belgique. Le but initial était de déterminer les caractéristiques du réservoir géothermique et la profondeur exacte de la série de calcaires du Carbonifère. Basé sur les résultats du puits exploration MOL-GT-01, un deuxième puits a été foré au printemps 2016, pour créer un doublet géothermique: un puits vertical (3610 m forés) et un puits dévié (4341m forés). Les deux puits ont fourni un éclairage nouveau du point de vue stratigraphique et structurel dans l'histoire géologique du Bassin de la Campine Belge. De plus, la presence d'un reservoir géothermique aux profondeurs supérieures à 2,500 m a été reconnu pour la première fois en Belgique, ouvrant des opportunités pour de nouveaux développements, ailleurs.

En el otoño del 2015 se perforó el primer pozo geotérmico profundo en el municipio de Mol, Bélgica. El objetivo principal fue explorar las características del yacimiento geotérmico y la profundidad exacta del Grupo Carbonífero Calcáreo. Se perforó un segundo pozo en la primavera del 2016, que fue basado en los resultados del pozo de exploración MOL-GT-01, creando un doblete geotérmico de un pozo vertical (3.610 m a lo largo del agujero) y un pozo desviado (4.341 m a lo largo del agujero). Ambos pozos proporcionan nuevas perspectivas estratigráficas y estructurales de la historia geológica de la Cuenca de Campine. Además la presencia de un embalse geotérmico a profundidades inferiores a 2.500 m ha sido demostrada por primera vez en Bélgica, abriendo así oportunidades para nuevos desarrollos en otros lugares.

Deep geothermal in Belgium

In Belgium four stratigraphic units exist that have been identified as potential geothermal reservoirs. These are, from youngest to oldest, the Chalk Group of Late Cretaceous age, the Buntsandstein Formation of Triassic age, the Neeroeteren Formation of Late Carboniferous age and the Carboniferous Limestone Group of Early Carboniferous age. Berckmans and Vandenberghe (1998) estimated the extractable thermal energy content of the four stratigraphic units at 11 EJ (***Table 1***). This estimate was based on a techno-economic maximal depth of 2,500 m.

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Today, geothermal wells targeting reservoirs at depths of 3,500 to 4,500 m are no longer exceptional (EGEC, 2014). In the context of the INTERREG-project GEOHEAT-APP, the extractable heat content of the four stratigraphic units has been recalculated (GEOHEAT-APP, 2014). The lower boundary was defined by a techno-economic evaluation that takes into account the expected thermal output of a geothermal doublet, the investment costs and the operational costs to extract the heat. This approach puts the techno-economic maximal depth for wells targeting the Carboniferous Limestone Group in the Campine region at 4,000 m. As for the estimate made by Berckmans and Vandenberghe, a minimal temperature of 25 °C and a recovery factor of 33% were used. Due to its deepest stratigraphic position and wide occurrence, the Carboniferous Limestone Group has the highest geothermal potential, with an estimated extractable heat content of 13 x 10^{18}J (***Table 1***). The higher estimates for the Carboniferous units is mainly due to the fact that the potential at depths below 2,500 m is also included.The geothermal potential of the Lower Carboniferous lime- and dolostones in Belgium was first described by Grosjean in 1954 based on the results of a coal exploration well in Turnhout. This well (17E225 in ***Figure 1***) showed an increased geothermal gradient (up to 50 °C/km) in the Upper Carboniferous shales overlying the limestones, and airlift tests revealed reservoir properties in the top of the limestones with permeabilities up to 1.5 Darcy at depths below 2,000 m. Wells in the vicinity of Loenhout (07E178 in ***Figure 1***) revealed even higher permeabilities (up to

Table 1: Recoverable thermal energy in selected geothermal reservoirs in Campine region assuming a return temperature of 25 °C and a recovery factor of 33%.

Geothermal aquifer	Recoverable heat (GJ)		Area (km²)
	Berckmans & Vandenberghe (1998)	GEOHEAT App (2014)	
Cretaceous chalks	1.77×10^9	0.46×10^9	2,185
Triassic sandstones	5.08×10^9	1.18×10^9	695
Neeroeteren sandstone	0.12×10^9	4.42×10^9	654
Lower Carboniferous limestone	4.45×10^9	13.02×10^9	3,120
Total	11.42×10^9	19.07×10^9	-

3.5 Darcy), however at shallower depths.

This led in the early eighties to exploration projects in Meer (07E225IIb in ***Figure 1***) and Merksplas (17W265 in ***Figure 1***). These were abandoned for various reasons before a doublet was installed (Vandenberghe, 1984; Vandenberghe *et al.*, 1988, 2000). Since then no new exploration initiatives have been taken. Up to this point the limestones were drilled to a maximum depth of 2,700 m. Measured formation water temperatures in a loss zone between 2,185 and 2,225 m were up to 103 °C (Grosjean, 1954).

Geological setting

Whereas the Lower Carboniferous geothermal reservoir is also present in the southern part of Belgium, all other potential geothermal reservoirs are only present in the northeastern part of the country, geologically known as the Campine Basin. The Campine Basin is part of the extensive Carboniferous basin of north-western Europe and its northern border is formed by the Krefeld high and IJmuiden ridge. Eastward the basin extends into Dutch Limburg, where the NE-SW striking Variscan Anticlinaal fault/Oranje fault system (***Figure 1***) forms the boundary with the German Carboniferous Wurm Basin. To the west and south, the basin is bounded by the subcropping early Palaeozoic rocks of the Caledonian London-Brabant Massif.

Predominantly clastic Devonian sediments unconformably overlie the Caledonian basement. The Devonian strata are covered by Early Carboniferous dolostones and limestones. In a large part of the basin, these carbonates are karstified and fractured. The transition from the Lower to the Upper Carboniferous is marked by a shift from a carbonate to a siliciclastic setting that is characteristic of the Late Carboniferous paralic coal basin of north-western Europe.

The area is transected by a predominant set of (N)NW - (S)SE striking normal faults, which locally display a shear component (***Figure 1***). Most of these faults already existed during the Early Carboniferous. Most faults were reactivated during the Jurassic, and some, e.g., the Feldbiss Fault and the Heerlerheide Fault, are still active today. A tectonic inversion of these reactivated faults during the Late Cretaceous and Early Cenozoic was followed by the subsidence of the Roer Valley Graben in the late Oligocene (Langenaeker, 2000). Locally, the (N)NW - (S)SE striking faults intersect with subordinate N-S to NE-SW striking thrust faults that are relicts of the compressional regime related to the Variscan uplift of the basin. The resulting pattern is one of a series of elongated, NW-SE striking fault blocks that are generally tilted towards the north/northeast. The tilting was caused by the uplift of the London-Brabant Massif during the Cimmerian orogenic phases (Langenaeker, 2000). This causes the Carboniferous subcrop to deepen quickly towards the north and northeast, and resulted in the preservation of the most complete Silesian sequence in northeast Limburg.

Results of the first deep wells

In 2010, the Flemish Institute for Technological Research (VITO) initiated a new two-dimensional seismic campaign covering the area between the cities of Turnhout, Herentals and Mol (see ***Figure 1***). Although the seismic data could be tied to well 30W371, which reaches the top of the Lower Carboniferous Limestone Group at a depth of 1,481 m below surface in Poederlee (***Figure 1***), uncertainties about the top reservoir interpretation were significant in the order of several hundreds of metres. This uncertainty resulted mainly from the correlation of the top-limestone seismic reflector over the faults downthrowing the limestones to the east between Poederlee and Mol-Donk. The seismic data pointed towards the presence of the Carboniferous Limestone Group at depths between 2,800 and 3,800 m at Mol-Donk.

A prospect was defined that could make use of potential reservoir improvement near a fault that affected the lower part of the Chalk Group and the older strata. A drilling location to drill a vertical exploration well towards the fault zone and the possibly fractured limestones and dolostones could be found on the Balmatt brownfield site that VITO acquired in Mol-Donk. Proving the potential of geothermal energy at this location and converting the brownfield into a greenfield with a geothermal power and heating plant would meet the sustainability goals of VITO.

On 14 September 2015 exploration well MOL-GT-01 was spudded. The start of the drilling activities was attended by over 300

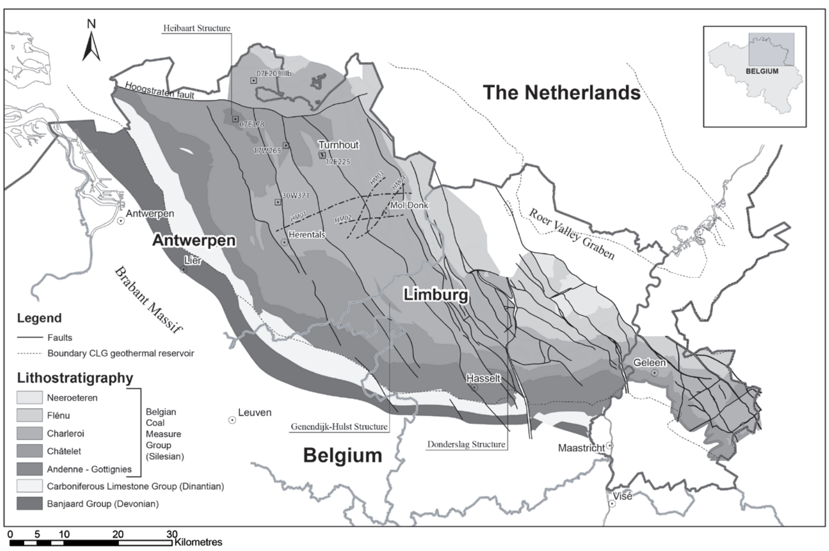

Figure 1: Palaeozoic subcrop map of the Campine Basin (compiled after Langenaeker, 2000; Patijn & Kimpe, 1961). The map shows the location of the Balmatt site at Mol-Donk, offset wells used to define the Balmatt geothermal project and the geometry of the 2D seismic campaign of 2010.

people, including several local and regional politicians, symbolic of strong public awareness. This well was financed by VITO and Flanders Innovation & Entrepreneurship (Agentschap Innoveren & Ondernemen). Additionally, NIRAS/ONDRAF co-funded the first section up to the base of the Cenozoic for their research in the field of nuclear waste storage.

The well architecture was designed with an anticipated top of the Lower Carboniferous Limestone Group at 2,800 m vertical depth. It was foreseen to drill the reservoir with an 8½” (216 mm) drill bit and to complete the reservoir section with an 7” (178 mm) partially slotted liner. However, the reservoir was encountered some 370 m deeper than anticipated. This led to drilling technical issues which resulted in loss of the lower 400 m of the 12¼” (311 mm) section. In order to be able to continue drilling, the upper part of the section was stabilised by running a 95/8” (244 mm) liner. Subsequently, a side-track, MOL-GT-01-S1, was drilled from the 95/8” (244 mm) liner

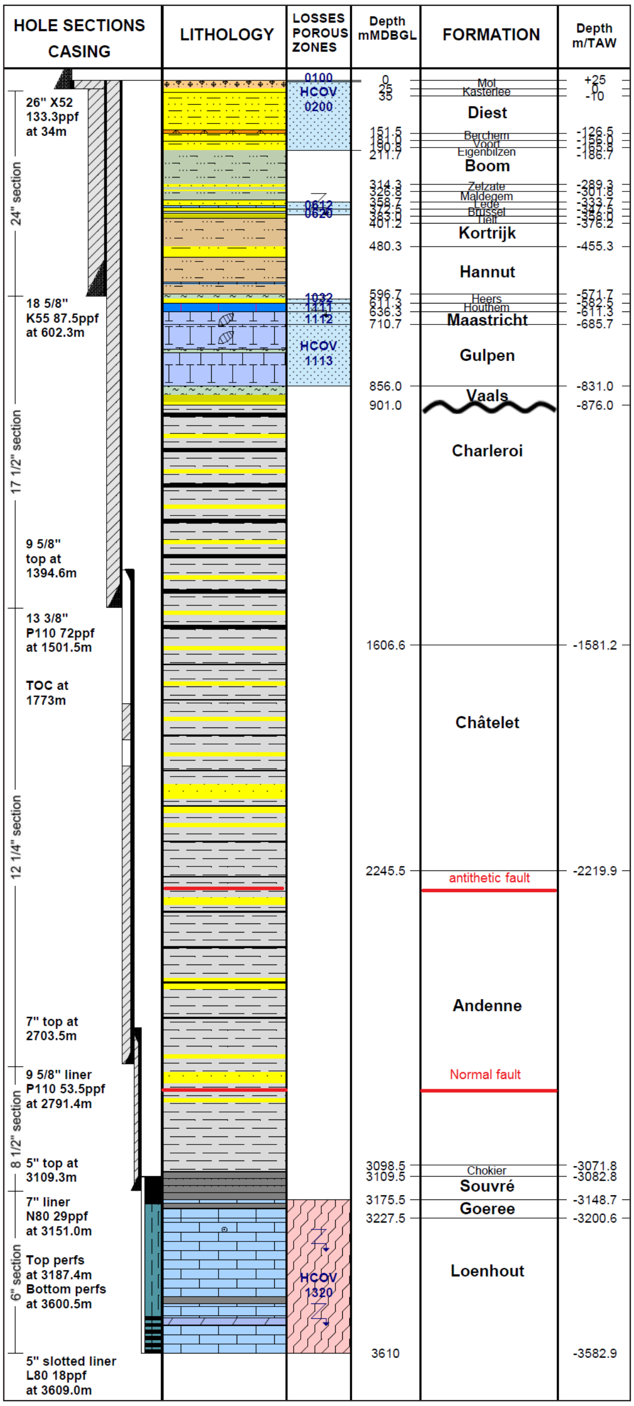

Figure 2: Geosummary of Well MOL-GT-01(-S1) with indication of well architecture on the left. Hole sections 24” (610 mm), 17½” (445 mm) and 12¼” (311 mm) and their casings are part of the original hole; the lowest two sections are part of the side-track. All aquifers are indicated with their respective HCOV-code (Hydrologische Codering Vlaanderen). Lithologies are based on cutting descriptions. TAW (Tweede Algemene Waterpassing) = regional reference level for Belgium.

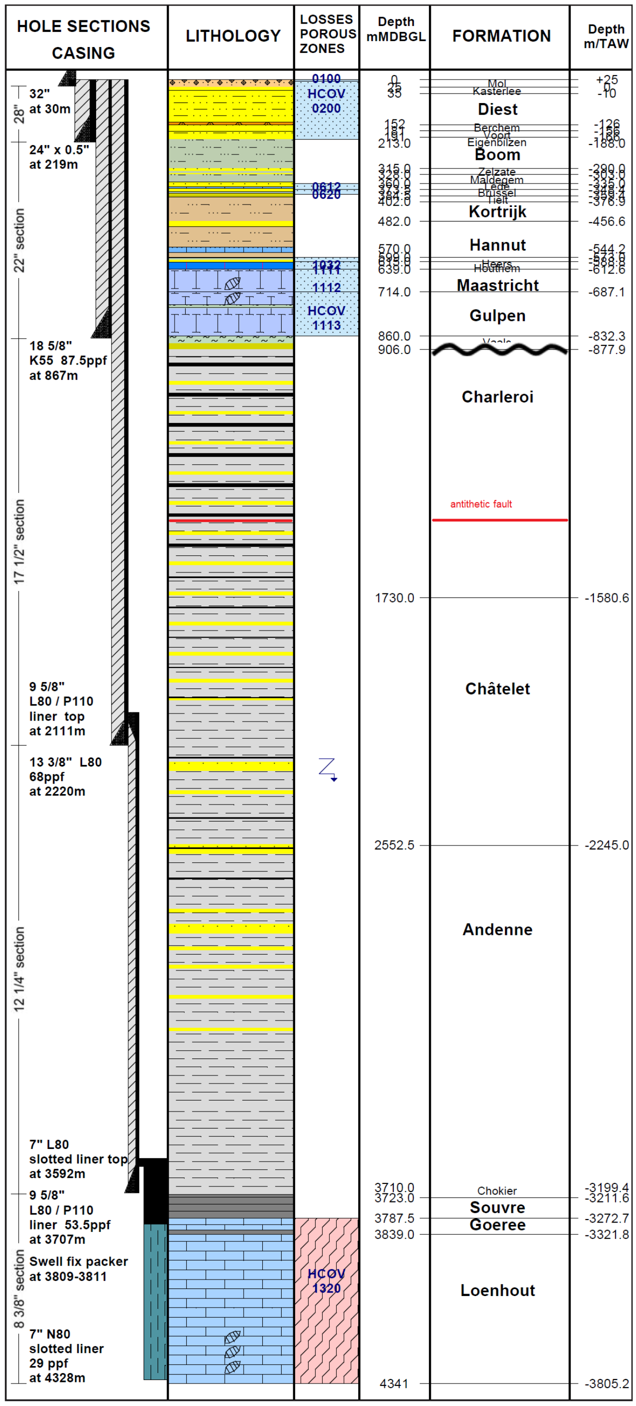

Figure 3: Geosummary of Well MOL-GT-02 with indication of well architecture on the left.

Table 2: Concentration of major and minor cations and anions measured in 2 downhole samples taken at 3,280 and 3,400 m in well MOL-GT-01-S1.

Parameter	Unit	MOL-GT01-3400m	MOL-GT01-3280m
Na^+	mg/l	49,800	49,600
K^+	mg/l	2,770	2,870
Ca^{2+}	mg/l	9,160	9,130
Mg^{2+}	mg/l	557	560
Sr^{2+}	mg/l	396	400
Ba^{2+}	mg/l	16.8	16.5
Fe^{2+}	mg/l	809	806
Mn^{2+}	mg/l	13.6	13.6
NH^{4+}	mg/l	267	264
Cl^-	mg/l	98,100	100,200
HCO_3^-	mg/l	1,117	1,129
SO_4^{2-}	mg/l	323	380
Br	mg/l	153	134
F^-	mg/l	< 0.88	< 0.88
pH		5.47	5.44
EC	mV	184.8	182.7

with an intermediate 8½" (216 mm) section that reached the top of the Carboniferous Limestone Group at a depth of 3,175 m. The limestones were drilled with a 6" (152 mm) bit down to 3,610 m and completed with a 5" (127 mm) slotted liner. Final well architecture of the well is given in ***Figure 2.***

Well MOL-GT-01-S1 was completed by 19 January 2016 and subsequently tested for its production capacity. While drilling the 6" (152 mm) section total mud losses were encountered, therefore indicating the presence of transmissivity at least in the immediate vicinity of the well. The production test confirmed the productivity with a calculated productivity index PI of 4 - 5m³/h/bar and production temperatures up to 128 °C.

The formation water is a Na(Ca)Cl brine with up to 165 g/l total dissolved solids. Sodium and chlorine sign for 90% of the dissolved ions. Besides, the water contains minor amounts of Ca^{2+}, Mg^{2+}, K^+, and $SO4^{2-}$. Downhole water samples reveal a pH of 5.4 for the formation fluid. The fluid is slightly reducing (redox potential SHE; 141–152 mV at 20 °C) and contains 800 mg/l dissolved iron (***Table 2***).

The gas content is about 2.5 Nm³ of gas per m³ of formation water. The main component is CO_2 (75–80% by volume). Besides, minor amounts of methane (8–11%), nitrogen (2–4%) and hydrogen (~11%) are present.

Based on the test results, VITO decided to drill a second well in the same location in order to be able to test a full geothermal doublet. Well MOL-GT-02 was spudded on 2 March 2016 and was drilled with an increasing angle up to an inclination of 40° in order to reach a distance from MOL-GT-01-S1 of at least 1,500 m at the top of the Carboniferous Limestone Group. MOL-GT-02 was deviated towards the NE, parallel to the seismic line MH10-04 and targeting a zone at the top of the reservoir in a more pristine area, not influenced by faults. The target for the second well was chosen in order to minimise the risk of fault activation when injecting large amounts of water and to investigate the reservoir characteristics of the limestones at larger distance from faults. The well was drilled without major drilling technical issues and along the planned well design (***Figure 3***). Again, the top of the Lower Carboniferous Limestones was found some 200 m deeper (at 3,300 m true vertical depth(TVD)) than predicted. The throw along the previously mentioned normal fault proved to be larger than anticipated.

MOL-GT-02 reached its final depth on 23 July 2016 at a depth of 4,341 m along hole. This corresponds to 3,830 m TVD. The well drilled through 530 m (true vertical) of limestones and dolostones and was completed with a 7" (178 mm) slotted liner (***Figure 3***). The well was tested for its injection capacity in September 2016, resulting in an injectivity index II of 1.5- 2 m³/h/bar. These values indicate rather poor reservoir conditions, which could be explained by the absence of a fault in the vicinity of this well.

Structural insights

The final structural interpretation is shown on the cross section in ***Figure 4***. The targeted normal fault was identified based on drilling parameters and fault mineralisations in the cuttings in both MOL-GT-01 as well as in MOL-GT-01-S1, resulting in an apparent dip of the fault plane towards the northeast. Both in MOL-GT-01 and in MOL-GT-02, a westerly dipping (antithetic) fault could be identified based on detailed correlations of the Upper Carboniferous sequences between both wells. All wells intersect the faults above the Lower Carboniferous reservoir level, however in MOL-GT-01-S1 the distance from the fault intersection to the top of the reservoir is only 300 m. From a calculated fault dip of 60°, the lateral distance to the fault at the top of the reservoir is some 175 m. Additionally, image logging (FMI, Schlumberger) performed over the reservoir in MOL-GT-01-S1 shows that several persistent fractures are present with a general NNW-SSE orientation, parallel to the assumed fault orientation. Accordingly, the presence of the fault near MOL-GT-01-S1 most probably

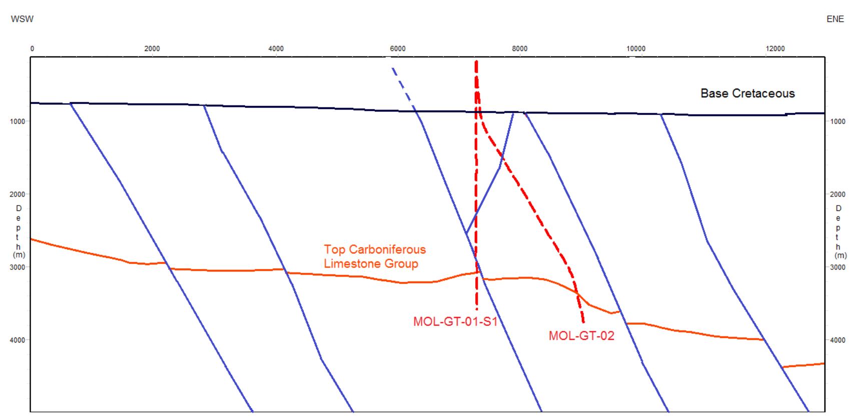

Figure 4: WSW-ENE depth section along strike of Well MOL-GT-02 with indication of the base Cretaceous (black) and top Carboniferous Limestone Group (orange) as well as the fault locations (blue) tied to both wells. Total length of the cross section is 13,000 m.

has improved the reservoir characteristics in this well; this conclusion is supported by the test results in MOL-GT-02, for which the distance to the nearest fault is roughly 1 km.

Future potential in the Campine Basin

The regional, cross-border potential of the Carboniferous Limestone Group was indicated in the GEOHEAT-APP report in 2014. However, for areas where the Lower Carboniferous strata are present at depths below 2,500 m, the risk of encountering poor or no reservoir conditions was still significant at the time of publication of the report. With the results of the first deep drillings at Mol-Donk, this risk has now been strongly reduced. The high potential zone suggested by the GEOHEAT-APP project can now be further explored and, if succesful, valorised.

The exploration drillings at the Balmatt site yield critical input for the business case of deep geothermal energy projects in the area. The results of the pumping tests indicate that the reservoir performance is sufficient to warrant further investment in a geothermal production unit at the Balmatt site, which is expected to provide heat for at least 20 years. Moreover, the production temperature is high enough to allow electricity production using binary technology. In order to explore the economics of low-temperature power generation in the Campine area, a prototype of a new, flexible binary unit will be installed at the Balmatt geothermal site.

The expertise and knowledge that have been gathered enable the drilling of additional wells to provide sustainable heat to neighbouring businesses and residential sites in an area covering the north-east of the Antwerp province and the northern half of the Limburg province. Depending on the effectiveness of further technological developments and the degree of implementation, between 10% and 25% of the Flemish energy (mainly heat) needs could be covered by local production (Laenen *et al.*, 2015).

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