Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 00 (2008) 000–000

Energy
Procedia

www.elsevier.com/locate/XXX

GHGT-9

CCS scenarios optimisation by spatial multi-criteria analysis: application to multiple source-sink matching in the Bohai Basin (North China)

Wenying CHEN[a], Fei TENG[a], Ruina XU[a], Xing XIANG[a], Rongshu ZENG[b],
Kim DOMPTAIL[c], Delphine ALLIER[c], and Yves-Michel LE NINDRE[c]*

[a] *Energy Environment and Economy (3E) Research Institute, Tsinghua University, Beijing 100084, China*
[b] *Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100049, China*
[c] *BRGM, BP 36009, Orléans, 45060 France*

Elsevier use only: Received date here; revised date here; accepted date here

Abstract

Methods, based on spatial analysis of the different criteria to be taken into consideration for building scenarios of CO_2 Capture and Storage (CCS), have been developed and applied to real case studies in the Hebei Province (northeast China). The total CO_2 emissions from point sources in the province amount to 220Mt/y, mainly from power plants, and from iron-steel, cement, ammonia plants, and refineries. Storage opportunities can be found in the Bohai Basin, characterised by a strong tectonic subsidence during the Tertiary, with several kilometres of accumulated clastic sediments. Two complementary methods were designed to best match sources and sinks, accounting for the cost of transport, injection and storage: an algorithm working on pairs of sources and sinks, and a spatial analyse on costs grids using functions of ArcGIS software which takes into account the additional costs of pipeline construction due to landform and land use.

Key words: Carbon capture and storage; Carbon emssion source; Storage Potentials; China; Bohai; Hebei;GeoCapacity

1. Introduction

Hebei province is selected as the first test region for carbon emission sources and storage potential assessment in China within the GeoCapacity, a three-year EU FP6 project starting from the beginning of 2006. It is geographically located between 36°05' to 42°37' North Latitude and 113°11' to 119°45 East Longitude lying in the North China Plain, encompassing Beijing and Tianjin, stretching to the Inner Mongolia Plateau, and facing the Bohai Sea to the east. It covers an area of 188,000 square kilometres with a population of more than 68 million. The topography of Hebei slopes down from northwest to southeast. Mountains, hills and highlands with scattered basins and valleys cover its territory in the northwest, while vast plains stretch over the central and south-eastern part of its land. Hebei

---

* Corresponding author. Tel.: +33 2 38 64 3496; fax: +33 2 38 64 3575.
E-mail address: ym.lenindre@brgm.fr.

Province boasts complete and adequate resources of energy, mainly as reserves of coal, petroleum and natural gas. The minerals resources are widely spread and present a complete distribution system which provides favourable conditions for establishing iron and steel industries, building materials industries, chemical industries bases in large scales and developing coal chemical, salt chemical and petrochemical industries.

2. Major carbon emission sources in Hebei Province

2.1. Methodology and main assumptions to estimate carbon emissions

In general, CO_2 emissions are calculated by multiplying fuel consumption by the corresponding emission factor. The emission factor for coal, oil, and natural gas is estimated as 0.715tC/tce, 0.548tC/tce, and 0.409tC/tce respectively. Fuel consumption for each carbon emission source is calculated by multiplying its production by the provincial average fuel consumption per unit production. For the coal-fired power plants in Hebei, the average gross coal consumption was 350 *gce/kWh* in 2004 and the corresponding carbon emission factor per unit production was thus estimated as 0.92 $ktCO_2/GWh$. Using the same approach, the average carbon emission factor per unit production for iron & steel, ammonia, and oil refinery is estimated as 1.94 $t\ CO_2/t\ steel$, 4.21 $t\ CO_2/t\ ammonia$, and 0.22 $t\ CO_2/t\ crude\ oil$ respectively. For cement, the average carbon emission factor of energy consumption is estimated as 0.474 $t\ CO_2/t\ cement$, and the average carbon emission factor of production process is estimated as 0.371 $t\ CO_2/t\ cement$ with the assumption that clinker consumption for producing one ton of cement is about 0.7 *t clinker/t cement* and average carbon emission factor for clinker is about 0.53 $t\ CO_2/t\ clinker$. Thus the average carbon emission factor for cement from energy consumption and production process totally is 0.845 $t\ CO_2/t\ cement$.

2.2. Carbon emission estimation for major point sources

The focus within this study is on large stationary source CO_2 emitters to which CCS might be applied, such as power plants, iron & steel, cement, ammonia, and oil refineries.

In 2004, 130 thermal power plants had a capacity over 6 MW. The average operation hours were 6350 hours per year and the average gross coal consumption rate was 350 gce/kWh. China is accelerating efforts to close small coal-fired units that use outdated technology and excessive energy. Consequently, we only selected the 42 power plants with capacity over 50 MW to estimate carbon emission. All these plants are coal-fired, and their total emission is estimated as 137 Mt of CO_2/yr.

In 2003, nine iron and steel plants had a total annual production of 24Mt steel. These nine plants are located in the city of Tangshan, Handan, Chengde, Xingtai, Zhangjiakou and Shijiazhuang. Tang Steel is the biggest enterprise among these nine iron and steel plants and the production was above 6 Mt steel in 2003. The amount of CO_2 emission from these nine sources was estimated at 47 Mt CO_2/yr.

In 2004, 386 cement production enterprises had total production of 88.5 Mt. Because of the huge pressure to save energy and resources, some medium and small producers were on the verge of being unprofitable and have been forced to close down. Moreover, the CO_2 emissions from the medium and small cement producers were relatively small and did not suit CO_2 capture. We selected 18 main enterprises whose total production was 31.4 Mt, accounting for 35% of Hebei's total cement production to estimate their carbon emissions. The total carbon emission from these 18 enterprises is estimated as 26.5 $MtCO_2$/yr.

In 2005, 50 ammonia production enterprises had a total production of 3.3 Mt. Among them there are 16 main enterprises whose total production is 1.9 Mt, comprising of 58% of the total. The amount of CO_2 emission from these 16 enterprises is estimated to be 8.1 Mt CO_2/yr.

In 2005, three oil refineries (Shijiazhuang refinery and Cangzhou refinery to SINOPEC and Huabei petrochemical company to PetroChina) produced 9.4 Mt of crude oil.. The scale of these three plants is similar. The amount of CO_2 emission from these 3 enterprises is estimated to be 2.1 Mt CO_2/yr.

Table 1 shows the breakdown of the estimated emission of CO_2 by sector in Hebei province. The total emission for these 88 sources is estimated as 220.7Mt CO_2/yr, with power, iron & steel, and cement sharing 62%, 21%, and 12% of the total respectively.

Table 1 - Large CO_2 Sources and Emissions by sector in Hebei Province

Type	Total enterprises		Enterprises estimated		CO_2 estimated	Share in total Emissions (%)
	Number	Annual production (Mt)	Number	Annual production (Mt)	(Mt CO_2/yr)	
Power Plant	130		42		137	62.08
Iron & Steel	9	24	9	24	47	21.30
Cement	386	88.5	18	31.4	26.5	12.01
Ammonia	50	3.3	16	1.9	8.1	3.67
Oil refinery	3	9.4	3	9.4	2.1	0.95
Total			88		220.7	100

3. CO_2 storage potential

The CO_2 storage potential was examined in the south of the Hebei province, and especially in the Jizhong depression. This potential can be found in the hydrocarbon fields in the buried hills and in the Tertiary, and in the tertiary aquifers, so long as they comply with the depth requirements.

3.1. Storage in hydrocarbon fields

Twenty five hydrocarbon fields have been selected from the Huabei complex. The total of Original Oil In Place is estimated at 880Mm^3, of which 458 Mm^3 is for the giant Renqiu alone and 2.3 Bm^3 gas. The ultimate oil recovery for Huabei (Laherrere [1]) would be 2.2 Gb or ~260 Mm^3 for Huabei, with a recovery factor of about 25% in the case of Renqiu. A recovery factor better than 60% could be expected for the gas. Table 2 describes their geological characteristics and location. Most of the selected fields belong to the buried hills type in fractured and karstified carbonate (mostly dolomite). The Wenan oil field is located in a Permo-Carboniferous sandstone. The selected Tertiary oil fields are located mostly in sandstone of the Oligocene Shahejie formation, and in the overlying Dongying formation. Although, through processes of “fault fracture mesh” (Zhang et al. [2]) the Miocene Guantao Formation is one of the most promising HC reservoir in the Bohai Basin, especially in Bozhong and Zhangua super-depressions, this type of field is not represented in the present selection. The ultimate recovery (UR), or volume at the surface, is used to estimate the equivalent maximum reservoir volume in which CO_2 can replace the extracted oil. This simplified estimate does not take into account Enhanced oil Recovery (EOR), and considers a nearly-depleted field.

The estimation of the CO_2 storage capacity in Mt was performed by using the following formula with the optimistic assumption that all the recovered HC could be replaced by an equivalent volume of CO_2 at reservoir conditions:

$$CO_2 = UR*FFV*\rho CO_2 = OGIP*RF\_G*FVF\_G*\rho CO_2 + OOIP*RF\_O*FVF\_O*\rho CO_2$$

where *OOIP* or *OGIP* is Original Oil/Gas In Place; *RF_O* or *RF_G* is recovery factor for oil/gas; *FVF_O/FVF_G* is formation volume factor for oil/gas; $\rho CO2$ is density of CO_2.

Accounting for recovery factor and for CO_2 density, the total Huabei complex exhibits a relatively low storage capacity of 215Mt CO_2, 182 corresponding to an equivalent oil volume, and 33 to an equivalent gas volume as shown in Table 2. The Renqiu field alone offers a potential of 83Mt. In fact the storage capacity would be less in real conditions of EOR.

Table 2 - CO2 storage potential assessment for the 25 selected oil/gas fields

Field name	HC type		Strat. Unit	Lithology	CO_2 oil. Mt	CO_2 gas. Mt	CO_2 tot. Mt	Cum. CO_2
Suning	Oil	Tertiary	Dongying	Sandstone	79.77	3.11	82.88	82.88
Chahejji	Oil		Dongying 2-Shahejie 1	Sandstone	20.67		20.67	103.56
Dawangzhuang	Oil		Dongying-Shahejie 1	Sandstone	4.28	15.68	19.96	123.52
Hexiwu	Oil		Shahejie 2-3	Sandstone	11.57		11.57	135.09
Liuchu	Oil		Shahejie 3	Sandstone	11.54		11.54	146.63
Liuquan	Oil		Shahejie 3	Sandstone	0.00	8.55	8.55	155.18
Bieguzhuang	Oil		Shahejie 4	Sandstone	7.09		7.09	162.27
Wenan	Oil		Permo-Carboniferous	Sandstone	6.84		6.84	169.11
Gaoyang	Oil	Ordovician	Ordovician	Dolomite, limestone	6.39		6.39	175.50
Guxinzhuang	Gas		Ordovician	Dolomite, limestone	5.13		5.13	180.63
Hezhuang	Oil		Ordovician	Limestone, dolomite	4.54		4.54	185.17
Hezhuangxi	Oil		Ordovician	Limestone, dolomite	4.27		4.27	189.44
Longhuzhuang	Oil		Ordovician	Limy dolomite	3.76		3.76	193.20
Nanmeng	Oil		Ordovician	Limy dolomite	3.76		3.76	196.96
Shenxi	Oil		Ordovician	Limestone, dolomite	0.00	3.11	3.11	200.07
Suqiao	Oil & Gas		Ordovician	Dolomite, limestone	2.71		2.71	202.78
Yongqing	Gas		Ordovician	Limestone, dolomite	2.24		2.24	205.02
Balizhuang	Oil	Precambrian	Jixian / Wumishan	Dolomite	2.16		2.16	207.18
Balizhuangxi	Oil		Jixian / Wumishan	Dolomite	2.07		2.07	209.25
Liubei	Oil		Jixian / Wumishan	Dolomite	1.88		1.88	211.14
Mozhou	Oil		Jixian / Wumishan	Dolomite	1.37		1.37	212.50
Renqiu	Oil & Gas		Jixian / Wumishan	Dolomite	0.74		0.74	213.25
Xuezhuang	Oil		Jixian / Wumishan	Dolomite	0.74		0.74	213.99
Yanling	Oil		Jixian / Wumishan	Dolomite	0.45		0.45	214.44
Hejian	Oil		Changcheng / Gaoyuzhang	Dolomite	0.23		0.23	214.67

3.2. Storage in aquifers: the Guantao Formation

The major aquifer systems of the Jizhong depression are located in the karstic fractured carbonates of the “Buried Hills” (Ordovician, Cambrian and Jixian-Wumishan group reservoirs, Wang Kun *et al.* [3]) and in the sandstones of the Tertiary clastic deposits. The Miocene Guantao Formation is the target aquifer for CO_2 storage.

3.2.1. Reservoir and cap rock

With a thickness of 60~700m, this formation consists of fluvial deposits. The depositional model comprises from east to west a transition from fine grained lacustrine deposits in the area of the present offshore Bohai Bay to meandering river (Zhanghua / Dongying depression), and to coarse grained braided river and alluvial fan in the west (Yang and Xu [4]). Vertically, it exhibits similarly a fining upward flooding sequence. Therefore, the best connectivity of the reservoir is expected in the Guantao 2 basal member and in the direction of the Jizhong depression. The cap rock consists of shales in the lower portion of the overlying Minghuazhen Formation.

Most of the deep structures differentiated since the beginning of the Tertiary had been filled at the end of the Paleogene and a major unconformity separates the Neogene from the older horizons. As shown by seismic sections (Zhao and Windley [5]), during the Neogene, four major sags controlled by fault blocks are still active along a central trough within the Jizhong depression: from south-west to north-east: Shenxian, Raoyang, Baxian and

Wuqing. Modelling of the Guantao geometry from published data (Allen *et al*. [6]); Petroleum Geology of Huabei field, [7]) indicates that storing CO_2 under a critical depth of 850m is possible within these blocks only (fig. 1).

The rock properties are good with porosity between 21-34% and permeability between 2-2500mD with an average of 250-450mD (Yang and Xu [4]). The net to gross ratio ranges between 25-75% in the Lower Guantao with a mean of 55% and 13-40% in the Upper Guantao with a mean of 20-27%, and 25-41% with a mean of 35-39 for the total Guantao Formation. The sandy horizons are generally 5-15m thick, and up to 20-30m by stacked genetic sequences of 5-7m each (Zhang *et al*. [2], Liu *et al*. [8], Guo and Chen [9]). The waters are of Cl - HCO_3- or HCO_3-Na /Na-Cl type, with a salinity of 1,000-3,600 mg/l. Water salinity increases with depth.

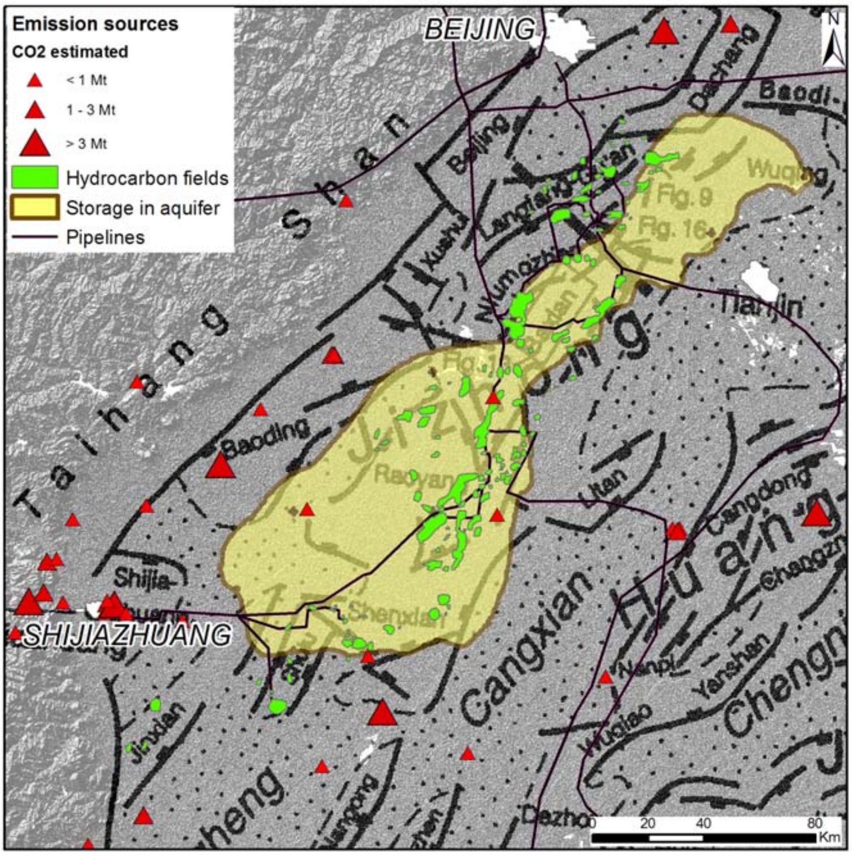

Figure 1 – Emission sources, pipelines, structures and storage opportunities in the Jizhong depression

3.2.2. Storage capacity

From our preliminary model, the surface covered by the Guantao Formation in the condition of storage (depth of top Guantao >850m, or base Guantao >1100m) is $12384Km^2$. Accounting for a mean thickness of 382m in the suitable area, a net to gross of 30% and a mean porosity of 25%, the pore volume in the sand for the total Guantao would be $355Mm^3$. Assuming that, in the worst case, due to tectonic and hydraulic confinement, no discharge from the aquifer system occurs during the CO_2 injection, the available volume would be created by water and pore compressibility assuming typical values of $6.10^{-5}bar^{-1}$ for pores and $4.4.10^{-5}bar^{-1}$ for water. Admitting a maximum over-pressure of 15 bars (~10% of the hydrostatic pressure), and a porosity of 25%, according to the equation $V_{CO2} = Vpores*(Cw+Cp)*\Delta p$ the storable volume of CO_2 would be 553Mm3 and the storage efficiency V_{CO2}/Vpores would be 0.16%. For a CO_2 density of 0.67 at a mean depth of 1400m, the corresponding CO_2 storage capacity $CMt=V_{CO2} *\rho CO2$ would be 371Mt only. In conclusion, CO_2 injection needs water discharge from the aquifer to store efficiently the CO_2 streams currently emitted. In that case, the pressure increase will be controlled in addition by the boundary conditions and the aquifer transmissivity T=k*e, i.e. by the diffusivity.

In a different hypothesis, considering a single sandy horizon with a thickness of 15m in the Lower Guantao with a net to gross ratio of 80%, assuming, by lack of data on hydraulic parameters, a storage efficiency of 3% due to water discharge (or pumping out), and accounting for isolated fault blocks corresponding to each sag, the mass of CO_2 stored would be 525Mt in Shanxian-Raoyang, 100Mt in Baxian, and 125Mt in Wuqing sag.

4. CCS scenarios optimization: CO_2 source sink matching models

Two models were developed: the first one is based on an algorithm working on pairs of sources and sinks, the second one is based on GIS cost grids.

4.1. First model (Xiang X, [10])

In the mapping model an algorithm is designed to best match sources and sinks depending on the cost of transport, injection and storage. The algorithm first calculates the cost for each possible combination of sources and sinks. To reduce the possibilities, it considers only the pairs in which the source and the sink are distant by less than a chosen radius. Then the source-sink pairs are ranked by increasing cost. Finally, starting with the cheapest pair, the algorithm checks whether the sink can accommodate N years of the sources emissions. If not, the algorithm moves on to the next pair. If the “N-year rule” is respected, the source is marked as “matched” and the N-year emissions of the source are deduced from the sink capacity. Then the algorithm moves on to the next pair. The costs of transport and injection are calculated following the methodology of Dahowski R.T, [11]. For transport, the cost of pipeline construction per km is multiplied by an estimated distance between the source and the sink. The distance is calculated as the straight-line distance plus an added constant of 10 miles, multiplied by a scaling factor of an additional 17%. Injection and storage costs include capital cost per well, operation and maintenance costs, and monitoring cost. These costs depend on the type of storage site: deep saline formations, depleted oil or gas field, or unmineable coal seam. Assuming operation and maintenance costs is 2% and 3% of investment cost for pipeline and injection well respectively, the annualized cost per unit length pipeline and per well can be calculated as:

$$AnnualUnitLengthCost = \left(\frac{r}{1-\left(\frac{1}{1+r}\right)^{N}} + 2\%\right) \times UnitLengthConCost$$

$$AnnualCostPerWell = \left(\frac{r}{1-\left(\frac{1}{1+r}\right)^{N}} + 3\%\right) \times Coef_{well} \times FormationDepth$$

Where r is discount rate, *UnitLengthConCost* is investment cost for pipeline per unit length which depends on CO_2 flow rate, $Coef_{well}$ is investment cost for well per unit depth, *FormationDepth* is depth of formation and the number of injection well is determined by the annual CO_2 capture with formation injectivity as:

$$InjWells = \frac{AnnualCO_2Captured}{Injectivity}$$

4.1.1. Second model

The first model can only provide us with a straight pathway between a source and a sink, the second model using ArcGIS software is designed to find the more realistic least-cost pathway between a source and a sink and to better estimate transport route and cost. It takes into account the additional costs of pipeline construction due to the slope of the terrain, the bypass of protected areas such as urban areas and national parks and the crossing of rivers, railways or highways. The methodology is to create a 90m*90m grid of cost where the value in each cell is the cost of pipeline construction across the cell. The base grid is the digital elevation model from USGS. Using the Raster calculator of ArcGIS we can then add different grids accounting for the location of the different obstacles. The matching can be based on several different criteria such as capture, transport, injection, storage/monitoring costs, emission source CO_2 quality, sink capacities. Capture is by far the most expensive step in the CCS process. For our modelling we do not take into account these costs and instead aim to minimize the total transport cost subject to sink capacities constraints. The first step is to estimate the transport costs. Then we design a GIS-based algorithm to calculate the least-cost pathways. Finally we take into account sink capacities.

The transport cost of CO_2 is approximated as the cost of pipeline construction and it is calculated as the sum of a basic cost of construction and an additional cost due to terrain conditions / obstacles. The basic cost of construction in RMB/km varies with the pipe diameter which depends on CO_2 flow rate.

Calculation of additional costs due to the slope of the terrain, the bypass of urban areas and the crossing of rivers are made with ArcGIS using 90m*90m grids. The slope of the terrain and the rivers are calculated using USGS 90m digital elevation data. Data on urban area are from ESRI. We sum the three grids according to the equation: Total Cost = Basic Cost (1 + a Slope + b Rivers + c Cities). And the cost factor for base case, slope 10%-20%, slope 20-30%, slope>30%, waterway crossing and populated place is 1, 0.1, 0.4, 0.8, 10 and 15 respectively (Herzog, [12]).

The model (shown in Figure 2) uses ArcGis Spatial Analyst tools: Cost Distance, Cost Backlink and Cost Path. The inputs are the grid of cost, the CO2 emission sources and the sinks database. The output is the least-cost pathway between each source and its cheapest sink to reach.

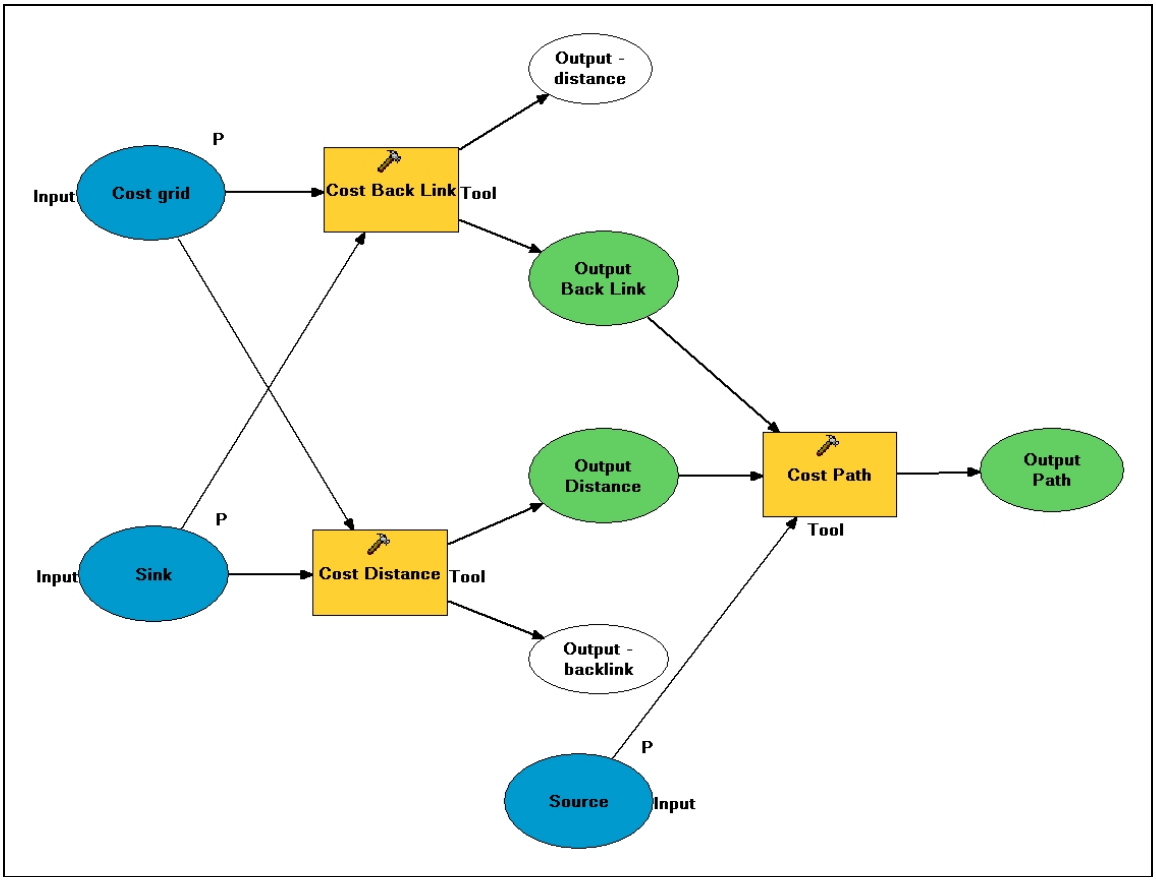

Figure 2 - ArcGis Model builder

Once the paths are calculated Access software is used to account for sink capacities. The pairs are ranked by increasing costs and we check whether the sink can accommodate N-year of the source emissions. If not, the next pair is considered. If the "N-year rule" is respected, the source is marked as "matched" and the N-year emissions of the source are deduced from the sink capacity. Then we move on to the next pair. Figure 3 displays the results.

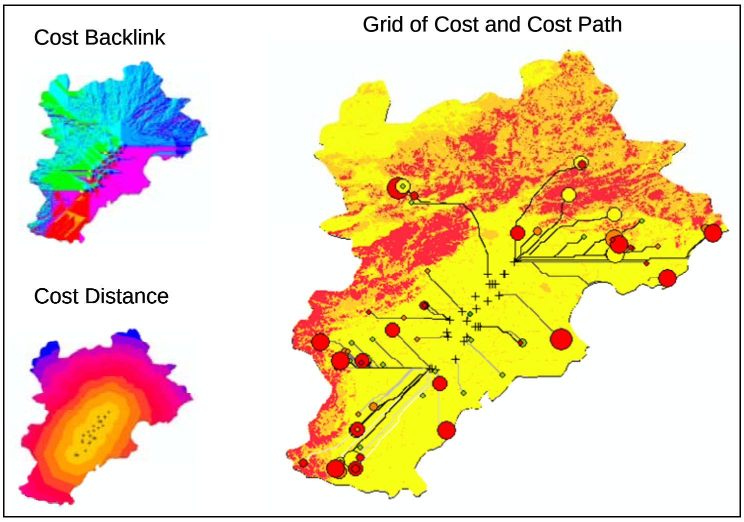

Figure 3 - Cost Backlink, Cost Distance and Cost Path results for 25 HC sinks and 88 sources in Hebei

5. Conclusions

Several improvements to the current mapping models will cover more friendly interfaces, better cost estimation for transportation and injection, consideration of capture cost, more accurate data for storage potential assessment, and combinations between costs and risks grids providing a useful Decision Support System, for CCS applications.

Acknowledgements

This study was supported by grant n°FP6-518318 of the European Commission, and of the French ANR (Agence Nationale pour la Recherche, Instituts Carnot) and performed in the framework of the Work Package n° 6 "International Cooperation" of the EU GeoCapacity Project. Special thanks to N.P. Christensen, T. Vangkilde-Pedersen, F. Dalhoff and N. Smith for their helpful contribution to the project in Beijing.

References

1. J. Laherrere. Questions to Feng Lianyong on the OGJ 14 Jan.2008 article :"Peak oil models forecast China's oil supply, demand" http://aspofrance.viabloga.com/files/JL_Q-OGJ14Jan08.pdf, 2008.
2. S. Zhang, Y. Wang, D. Shi, H. Xu, X. Pang, and M. Li. Fault fracture mesh petroleum plays in the jiyang superdepression of the Bohai Bay Basin, easter China. Marine and Petroleum Geology, 21, pp. 651-668, 2004
3. K. Wang, C. Li and H. Lei. The sustainable development and utilization of geothermal resources in Tianjin, China. Proceedings World Geothermal Congress, Antalya, Turkey, 24-29 April 2005.
4. Y. Yang Y. and T. Xu. Hydrocarbon habitat of the offshore Bohai Basin, China. Marine and Petroleum Geology, 21, pp. 691-708, 2004.
5. Z.Y Zhao and B.F. Windley. Cenozoic tectonic extension and inversion of the Jizhong basin, Hebei, northern China. Tectonophysics, 185. pp. 83-89, 1990
6. M.B. Allen, D.I.Macdonald, Z. Xun., S.J. Vincent, and C. Brouet-Menzies. Early Cenozoic two phase extension and late cenozoic thermal subsidence anf inversion of the Bohai Basin, northern China. Marine and Petroleum geology. Vol. 14, N°7/8, pp. 951-972., 1997.
7. Petroleum Geology of Huabei Oilfield, Petroleum Geology of China (Vol. 5). Petroleum Industry Press, Beijing, 1993
8. X. Liu; Y Lu, S. Cheng, and G. Hu. High Resolution Stratigraphy Study on Fluvial Deposit of Guantao Formation in Kenxi Oil Field. Acta Sedimentologica Sinica, Vol. 20, N°1, pp. 101-105, 2002.
9. Guo Q. and Chen J. Sedimentary model of braided river of Guantao Formation in Gaoshangbao oilfield. Erat Sciences. Journal of China University of Geosciences, Vol. 22, N°5, pp. 552-556, 1997.
10. X. Xiang,. China CCS Database and Application of CO_2 Source Sink Mapping Model. Dissertation paper for Master degree. Beijing: Tsinghua University, 2007.
11. R.T. Dahowski, J.J. Dooley, C.L. Davidson, S. Bachu, and N. Gupta N. A CO_2 Storage Supply Curve for North America. Battelle, prepared for IEA Greenhouse Gas R&D Programme. 2004.
12. H. Herzog. A GIS-based model for CO_2 pipeline transport and Source-Sink Matching Optimization Westcarb Annual Business Meeting, Phoenix AZ http://www.westcarb.org/Phoenix_pdfs/finalpdfs-11-08-06/17-Herzog_GIS.pdf. 2006.