ELEKTROINŠTITUT MILAN VIDMAR

ELECTRIC POWER RESEARCH INSTITUTE

CO_2 CAPTURE READINESS OF UNIT 6 IN THERMAL POWER PLANT ŠOŠTANJ

(Addition)

Paper Nr.: 2034

Ljubljana, September 2010

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SUMMARY

A study "CO_2 capture readiness of unit 6 in Thermal power plant Šoštanj" prepared in June 2010 confirms that Unit 6 of Power plant Šoštanj fulfils requirements of capture readiness defined in European legislation.

An addition to the study in greater detail analyzes availability of CO_2 storage sites in Slovenia, nearby countries and North Sea. Their availability and appropriate capacity are the condition of retrofitting CCS to the Unit 6 of Thermal power plant Šoštanj. This will produce from 70,2 to 76,2 Mio.t of captured carbon dioxide in the period from the year 2020 to 2054. Analyzes demonstrates that Slovenia has underground aquifers with total capacity about 92 Mt. It is sufficient to store CO_2 captured on Unit 6. Besides there is coal mine near the plant. It also represents a potential additional storage site which is under investigation. Storage sites in nearby countries like Croatia and Italy have large storage capacities and are in radius of 350 km. That is close enough not to make high transport cost. Another possible solution offers port Koper at the Adriatic Sea. From there it is possible to transport compressed CO_2 to suitable locations in North Sea or elsewhere by ships.

Economical parameters of retrofitting carbon capture and storage technology to Unit 6 like investment cost, operational & maintenance cost, transport and storage cost are analyzed. Cost originating from loss of power production is also considered. All of them are expressed in Euros per unit of generated electricity (€/MWh). When CO_2 is mainly stored in Slovenian deep onshore aquifers the total cost of CCS is in range from 29,0 to 39,9 €/MWh and the representative value is 31,6 €/MWh. In the case when CO_2 has to be transported to locations about 250 km from the source and stored in onshore aquifers the cost is from 29,8 to 40,8 €/MWh and the representative cost is 32,5 €/MWh. Total carbon capture and storage cost could be even higher if the distances to storage sites are longer, the transport is carried out by offshore pipelines or by ships and the storing is done in offshore aquifers.

The cost of electricity generation that originates from CCS is compared with the cost that is based on price of CO_2 allowances. Considering the lowest CCS cost implementation to Unit 6 of Thermal power plant Šoštanj (storage in Slovenian onshore aquifers) is in range of cost originating from emission trading when CO_2 allowance costs more than 33 €. In case of highest carbon capture and storage cost (storage in onshore aquifers 250 km from Unit 6) the point where CCS yields more than emission trading is at 46 € per CO_2 allowance.

Addition to the study "CO_2 capture readiness of unit 6 in Thermal power plant Šoštanj" shows that storage sites for permanent disposal of carbon dioxide are available and have sufficient capacity. Cost analyzes confirms that retrofitting carbon capture and storage technology to Unit 6 of Thermal power plant Šoštanj is economically feasible and in range with cost induced by emission trading.

Key words:

Thermal power plant Šoštanj, Unit 6, carbon capture and storage, post combustion capture, transport, storage, capture ready, investment cost, operational and maintenance cost, transport cost, storage cost, allowance

1. INTRODUCTION

In May 2010 a study "CO_2 capture readiness of unit 6 in Thermal power plant Šoštanj" was prepared. It focused on carbon capture and storage legal requirements and carbon capture technology. It compares pulverized coal combustion power plant's technical characteristics with requirements necessary to retrofit CCS to Unit 6. It also analyzed possibilities of transporting and storing of captured carbon dioxide as well as environmental impacts of potentially intended investment. The study confirmed that Unit 6 of Thermal power plant Šoštanj fulfils requirements of capture readiness defined in European legislation.

In September 2010 an addition to the study is prepared. It in greater detail analyzes availability of CO_2 storage sites in Slovenia, nearby countries and North Sea. Their availability and appropriate capacity are the condition of retrofitting CCS. In this frame onshore and offshore saline aquifers as well as depleted oil and gas fields and coal mines are examined. Above all their distance from Thermal power plant Šoštanj and their storage capacities are checked. On this basis their suitability for permanent disposal of carbon dioxide captured on Unit 6 of Thermal power plant Šoštanj is estimated.

In addition to the study economical parameters of retrofitting carbon capture and storage technology to Unit 6 are analyzed too. In this part investment cost, operational and maintenance cost and transport and storage cost are calculated. Cost originating from loss of power production is also considered. All of them are expressed in Euros per unit of generated electricity (€/MWh). On this evaluation is based economic feasibility of retrofitting CCS.

Analyzes dedicated to availability of storage sites and economic evaluation of retrofitting CCS to Unit 6 of Thermal power plant Šoštanj confirm, that Unit 6 is capture ready from this points of view too.

2. STORAGE SITES

2.1 Storage sites in Europe

There are several ongoing international projects in Europe. Their goal is to estimate storage capacities for permanent storage of CO_2 within the EU territory. Preliminary estimates, obtained within the framework of the GoeCapacity project, indicate that storage capacities in Europe far exceed the emitted quantities of carbon dioxide from large point sources. The results of the GeoCapacity project are the first detailed pan-European assessment of CO_2 storage capacity. The GIS database include a total storage capacity of 360 Gt with 326 Gt in deep saline aquifers, 32 Gt in depleted hydrocarbon fields and 2 Gt in unmineable coal beds. 116 Gt is onshore storage capacity and 244 Gt is offshore storage capacity. Almost 200 Gt of the total storage capacity in the database is located offshore Norway. In Figure 1 CO_2 emission sources and storage locations in Europe are shown.

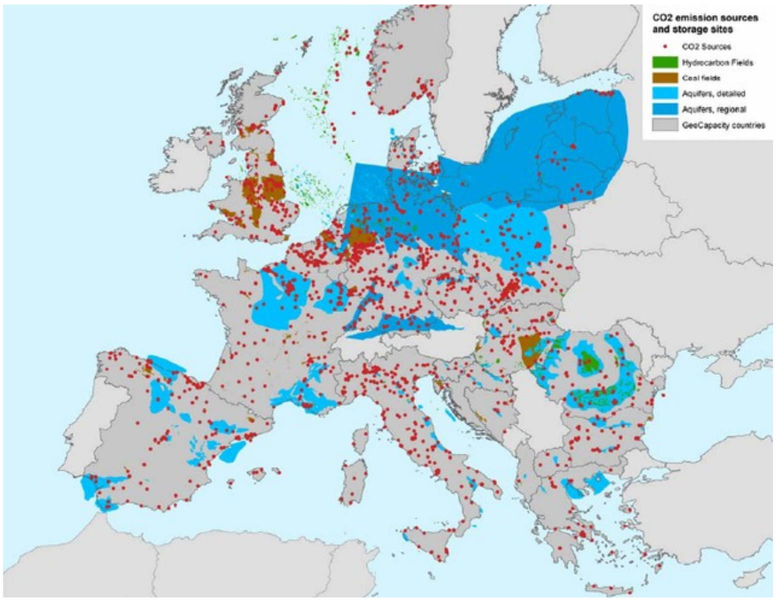

Figure 1: CO_2 emission sources and storage locations in Europe

In the table 1 more cautious and conservative estimates for each European country are provided. This figure probably gives the most realistic picture of storage capacity that can be realized in Europe.

Table 1: European summary of CO_2 emissions and storage capacity estimates

Country	**Annual total CO_2 emissions (Mio.t)**	**Annual CO_2 emissions from large point sources (Mio.t)**	**CO_2 storage capacity in deep saline aquifers (Mio.t)**	**CO_2 storage capacity in hydrocarbon fields (Mio.t)**	**CO_2 storage capacity in coal fields (Mio.t)**
Slovakia	46	23	1716	-	-
Estonia	21	12	-	-	-
Latvia	4	2	404	-	-
Lithuania	18	6	30	7	-
Poland	325	188	1.761	764	415
Czech Republic	128	78	766	33	54
Hungary	79	23	140	389	87
Romania	74	67	7.500	1.500	-
Bulgaria	52	42	2.100	3	17
Albania	0	0	20	111	-
FYROM	6	4	390	-	-
Croatia	23	5	2.710	189	-
Spain	423	158	14.000	34	145
Italy	212	140	4.669	1.810	71
Slovenia	20	7	92	2	-
Bosnia-	29	9	197	-	-
Germany	864	465	14.900	2.180	-
Luxemburg	11	-	-	-	-
Netherlands	180	92	340	1.700	300
France	372	131	7.922	770	-
Greece	110	69	184	70	-
United	555	258	7.100	7.300	-
Denmark	52	28	2553	203	-
Norway	43	28	26.031	3.157	-
Belgium	103	58	199	-	-
Total	**3.750**	**1.893**	**95.724**	**20.222**	**1.089**

The sum of the conservative storage capacity estimates is 95,7 Gt CO_2 in deep saline aquifers, 20,2 Gt in depleted hydrocarbon fields and 1,1 Gt in unmineable coal beds. This totals 117,0 Gt CO_2 of conservative European storage capacity. Approximately 25% of these is offshore Norway in mainly deep saline aquifers.

Total annual emissions of CO_2 from large point sources emitting more than 0.0001 Gt/year are 1,893 Gt. Conservative storage capacity estimates of 117,035 Gt CO_2 in comparison with total emissions correspond to 62 years of storage.

2.2 Storage sites and researches in Slovenia

Environment protection, increase of economic efficiency of the carbon dioxide capture and storage process and, not lastly, increased public acceptance of the CCS technology are the aims being pursued at researches pointed towards search of suitable locations for permanent storage of captured CO_2in Slovenia. Slovenia is integrated in international programs that research possibilities of carbon capture and storage. At the same time researches are dedicated to find out the appropriate storage sites on Slovenian territory.

In the frame of GeoCapacity project Slovenian potential storage capacities were investigated too. The potential of storing CO_2 underground in Slovenia exists in aquifers as well as in depleted oil/gas fields. The option to store in unmineable coal layers should not be neglected, but further investigations are necessary. The best potential is expected in aquifers. Figure 2 shows CO_2 emission sources and locations of storage capacities in Slovenian aquifers.

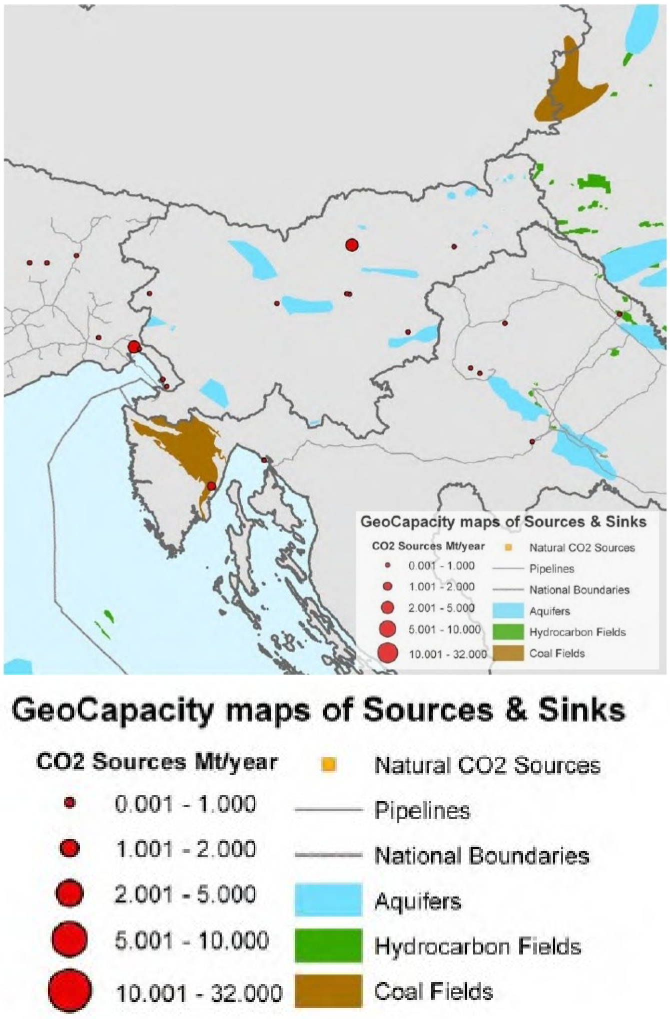

Figure 2: Map of CO_2 emissions, infrastructure and storage capacity in Slovenia.

Estimation of storage capacities is based on parameters like area, thickness, porosity, storage efficiency factor etc… Depending on used ranges of calculation parameters minimum and maximum values are obtained. Conservative estimate for storage capacity in aquifers is 92 Mio.t CO_2, while the optimistic value exceeds 500 Mio.t.

In the table 2 more cautious and conservative estimates are provided.

Table 2: CO_2 emissions and storage capacity estimates in Slovenia

CO_2 emissions	**Year(s)**	**Average CO_2 emissions (Mio.t)**
CO_2 emissions from large point sources in database	2005	7
Total CO_2 emissions	2005	20

CO_2 storage capacity	**Pyramid class**	**Conservative estimate (Mio.t)**
Storage capacity in aquifers	Effective (Theoretical in some cases)	92
Storage capacity in hydrocarbon fields	Theoretical / effective	2
Storage capacity in coal fields	Not included	Not included
Total storage capacity estimate	**Theoretical / Effective**	**94**

Storage capacity in coal layers is not included in table but it should not be neglected. In Slovenia there are some coal seams. One of them is situated just near the Thermal power plant Šoštanj. Some investigations were carried out in the past years, but further researches are necessary to prove the possibility of captured CO_2 storing.

Unit 6 of Thermal power plant Šoštanj will be the largest Slovenian point source of CO_2. It will operate from the end of 2014, when a trial operation will begin, until expiration of its life span in the year 2054. In the period from 2020 till 2054 101.717 GWh of electricity will be generated and at the same time expected CO_2 emission from Unit 6 will amount 86,6 Mio.t. In calculations efficiency of carbon capture process from 81 to 88 % is taken into account. Representative value is 85 %. Total amount of captured carbon dioxide varies from 70,2 to 76,2 Mio.t and the representative value is 73,6 Mio.t during 34 years of operation. Conservative estimate of storage capacity in aquifers is 92 Mio.t CO_2, while the optimistic value exceeds 500 Mio.t. Regarding this Slovenian available storage capacity is sufficient to store all CO_2 captured on Unit 6.

Environment protection, increase of economic efficiency of the carbon dioxide capture and storage process and, not lastly, increased public acceptance of the CCS technology are the aims being pursued at researches pointed towards search of suitable storage locations in Slovenia. Thermal power plant Šoštanj is definitely interested in storing of captured carbon dioxide on Slovene territory. Researches are carried out to find suitable geological structures, if possible, in vicinity of the source, for permanent storing of captured carbon dioxide. The potential possibilities are:

- deep saline aquifers,
- depleated oil fields and
- ECBM (Enhanced Coal-Bed Methane) technology.

The researches conducted by the Thermal power plant Šoštanj in consortium, together with other interested partners, are aimed to CO_2 storage suitability analysis on the territory of Coalmine Velenje with the ECBM technology. Other suitable geological structures that would enable permanent storage of captured CO_2 are investigated too.

The figure 3 below shows a trial injecting of carbon dioxide on the territory of mining area of Coalmine Velenje, which is located in the vicinity of the Thermal power plant Šoštanj.

Figure 3: A trial injecting of carbon dioxide on the territory of mining area of Coalmine Velenje
(Photo: Orešnik, 2005) (Source: Pregled dosedanjih raziskav na področju možnosti shranjevanja ogljikovega dioksida v Šaleški dolini, ERICo Velenje, Inštitut za ekološke raziskave, Velenje, junij 2006)

Additional researches are carried out to obtain additional data necessary to estimate storage capacity.

If further researches prove that there is not enough suitable storage capacity in Slovenia, than the captured CO_2 should be stored at suitable locations in Europe respectively elsewhere in the world. Preliminary estimates of storage capacity, which are suitable for permanent storage of CO_2, indicate that the storage capacities themselves in Europe as well as elsewhere in the world are much greater than the emitted quantities of CO_2.

As the economy favors short transport distance Thermal power plant Šoštanj is definitely interested in storing captured carbon dioxide on the Slovene territory. In the case of lack of the storage capacity the storage should be done in the adjacent countries. Possible CO_2 storage opportunities in the countries just near the Slovenian border are given below.

2.3 Potential storage sites in the adjacent countries

2.3.1 Croatia

In the frame of EU project GeoCapacity was concluded that the Croatian territory is favorable for geological storage of CO_2. Storage capacity lies onshore, mainly in the southern part of the Pannonian basin and Adriatic offshore. Estimated storage capacity amounts from 2.899 Mio.t (conservative estimate) to 4.256 Mio.t (estimate in database). In the table 3 estimates are provided.

Table 3: CO_2 emissions and storage capacity estimates in Croatia.

CO_2 emissions		**Year(s)**	**Average CO_2 emissions (Mio.t)**
CO_2 emissions from large point sources in database		2003	5
Total CO_2 emissions		2003	23
CO_2 storage capacity	**Pyramid class**	**Conservative estimate (Mio.t)**	**Estimate in database (Mio.t)**
Storage capacity in aquifers	Theoretical	2.710	4.067
Storage capacity in hydrocarbon fields	Effective	189	189
Storage capacity in coal fields	Not included	-	-
Total storage capacity estimate	Theoretical	2.899	4.256

Storage capacity in coal layers is not included in the table because of the lack of the informations of the unmined parts.

Croatian CO_2 emission from large point sources amounts about 5 Mio.t per year. Conservative estimate for storage capacity in aquifers and hydrocarbon fields is 2.899 Mio.t CO_2. Regarding this Croatian storage capacity far exceeds their CO_2 emissions. Conservative storage capacity estimates in comparison with total emissions from large point sources correspond to 580 years of storage.

Taking into account storage capacity and vicinity to the Thermal power plant Šoštanj Croatian territory is suitable for storing CO_2 captured on Unit 6.

In figure 4 CO_2 emissions, infrastructure and storage capacity in Croatia are shown.

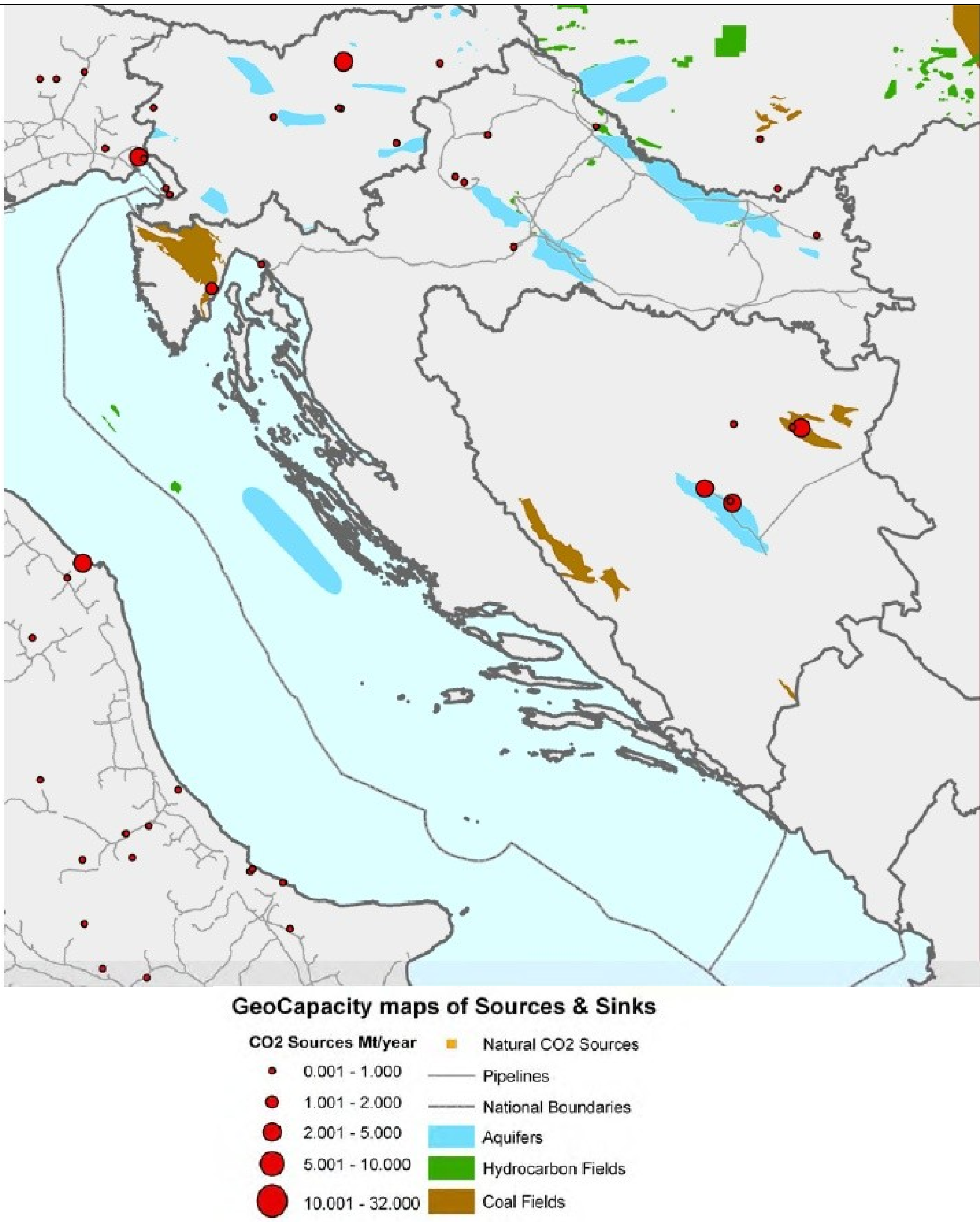

Figure 4: Map of CO_2 emissions, infrastructure and storage capacity in Croatia

2.3.2 Hungary

Hungary, which is dominantly covered by sedimentary basins has several available geological storage options (i.e., saline aquifers, depleted hydrocarbon fields, coal seams). The largest possible storage sites could be attributed for the deep saline aquifers. Basic estimation of storage capacity evaluated in the frame of GeoCapacity is presented.

For hydrocarbon reservoirs the storage capacity of 408 Mio.t was estimated. In case of saline aquifers the storage capacity ranges between 140-560 Mio.t depending on the magnitude of the used efficiency factor. Estimated storage capacity of unmineable coal seams amount around 87 Mio.t. Total estimated storage capacity in hydrocarbon fields, saline aquifers and coal seams amount from 616 Mio.t (conservative estimate) to 1.037 Mio.t (estimate in database). In the table 4 cautious and conservative estimates are provided.

Table 4: CO_2 emissions and storage capacity estimates in Hungary.

CO_2 emissions		**Year(s)**	**Average CO_2 emissions (Mio.t)**
CO_2 emissions from large point sources in database		2005	23
Total CO_2 emissions		2006	79
CO_2 storage capacity	**Pyramid class**	**Conservative estimate**	**Estimate in database**
Storage capacity in aquifers	Theoretical	140	561
Storage capacity in hydrocarbon fields	Effective	389	389
Storage capacity in coal fields	Effective	87	87
Total storage capacity estimate	**Effective**	**616**	**1037**

Hungary's CO_2 emissions from large point sources amount about 23 Mio.t per year. Conservative estimate for storage capacity in aquifers, hydrocarbon fields and coal fields is 616 Mio.t CO_2. Conservative storage capacity estimate in comparison with total emissions from large point sources corresponds to 27 years of storage.

Some of the storage capacity is situated just near or very close to the Slovenian border. As the distance from the Thermal power plant Šoštanj to those storage sites is not so long, those storage sites are also appropriate for storing CO_2 captured on Unit 6.

In figure 5 CO_2 emissions and storage capacity in Hungary are shown.

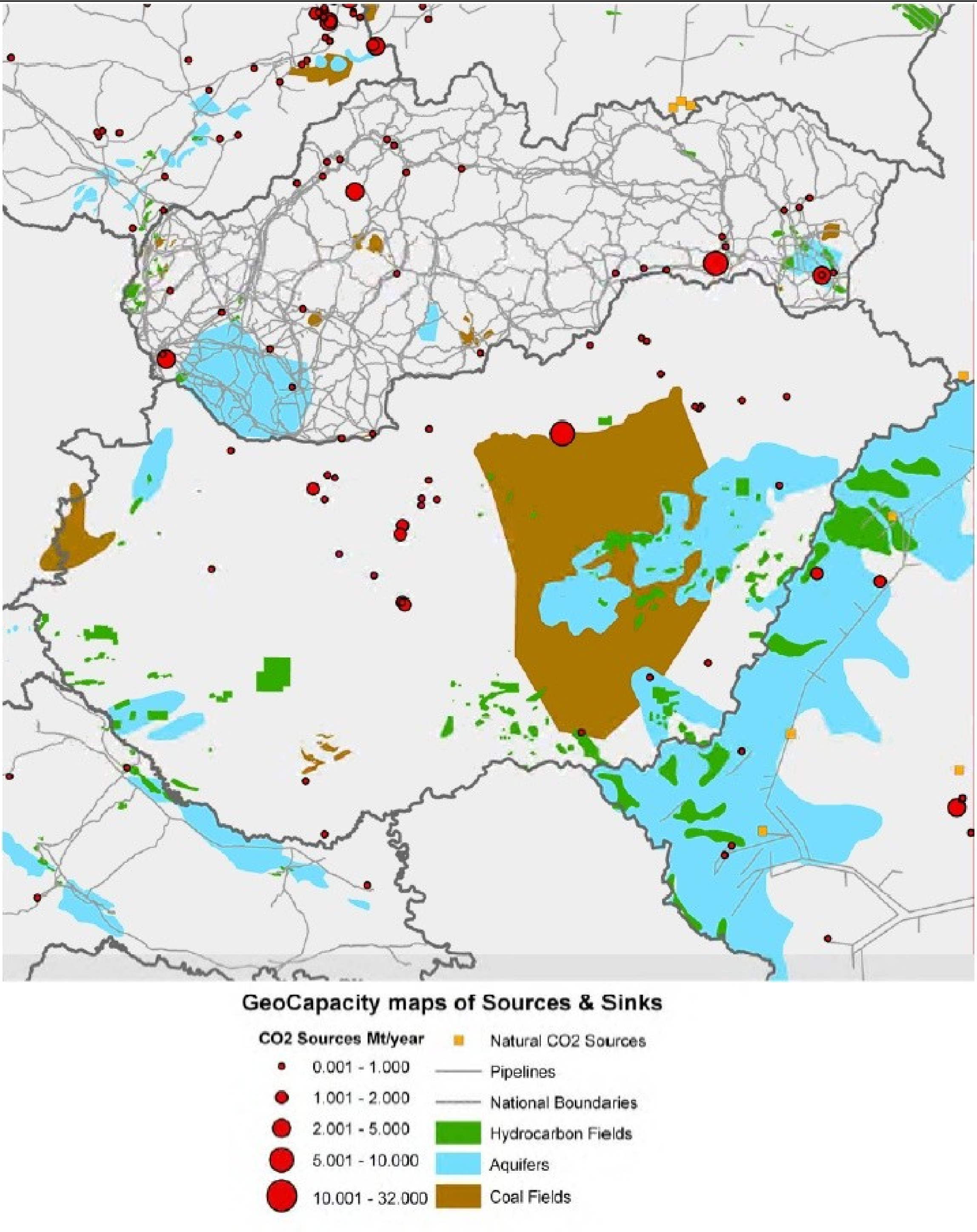

Figure 5: Map of CO_2 emissions and storage capacity in Hungary

2.3.3 Italy

Italy has several available geological storage options (i.e., saline aquifers, depleted hydrocarbon fields, coal seams). The largest possible storage capacity could be attributed to the deep saline aquifers.

For hydrocarbon reservoirs a conservative storage capacity of 1810 Mio.t was estimated. In case of saline aquifers the storage capacity ranges between 4.669 – 9.339 Mio.t depending on the magnitude of the used efficiency factor. Estimated conservative storage capacity of unmineable coal seams amounts around 71 Mio.t. Total estimated storage capacity in hydrocarbon fields, saline aquifers and coal seams amounts from 6.550 Mio.t (conservative estimate) to 13.031 Mio.t (estimate in database). In the table 5 more cautious and conservative estimates are provided.

Table 5: CO_2 emissions and storage capacity estimates in Italy

CO_2 emissions	**Year(s)**		**Average CO_2 emissions (Mio.t)**
CO_2 emissions from large point sources in database (> 1 Mio.t/year)	2004		140
Total CO_2 emissions	2004		212
CO_2 storage capacity	**Pyramid class**	**Conservative estimate (Mio.t)**	**Estimate in database (Mio.t)**
Storage capacity in aquifers	Effective	4669 (Seff : 2%)	9339 (Seff : 4%)
Storage capacity in hydrocarbon fields	Theoretical	1810	3427
Storage capacity in coal fields	N/A	71	265
Total storage capacity estimate		**6550**	**13031**

Italy's CO_2 emissions from large point sources amount about 140 Mio.t per year. Conservative estimate for storage capacity in aquifers, hydrocarbon fields and coal fields is 6.550 Mio.t CO_2. Conservative storage capacity estimates in comparison with total emissions from large point sources corresponds to 47 years of storage.

Some of the storage capacities are situated just near or very close to the Slovenian border. As the distance from the Thermal power plant Šoštanj to those storage sites is not so long, those storage sites are also appropriate for storing CO_2 captured in Thermal power plant Šoštanj.

In figure 6 CO_2 emissions and storage capacity in Italy are shown.

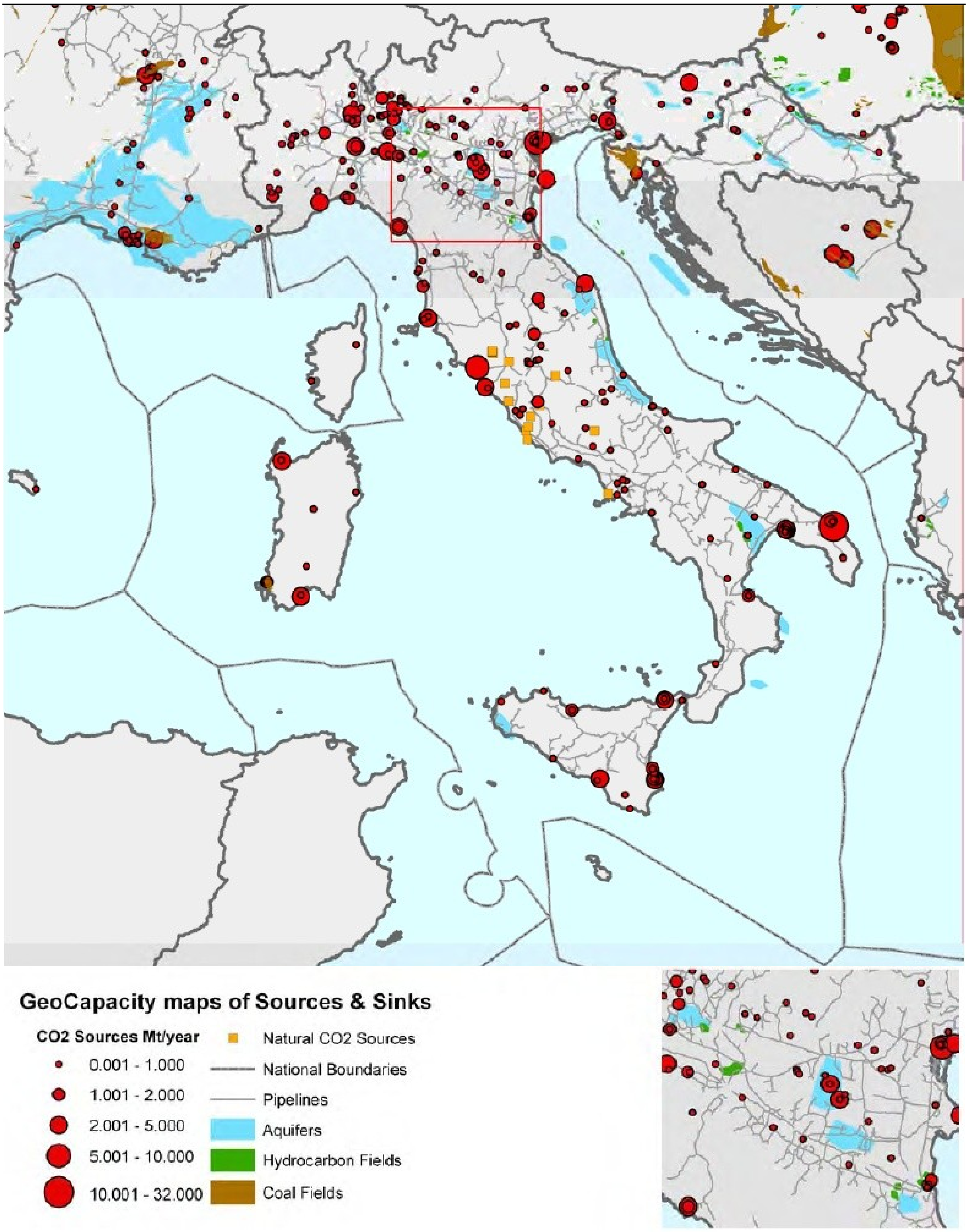

Figure 6: CO_2 emissions, infrastructures, CO_2 natural sources and storage capacity in Italy

Location of the promising potential Adriatic offshore storage capacity which was not included in the Geocapacity estimations is shown in the figure 7. Estimated storage capacity amounts 1.300 Mio.t. This storage site is according to it's location and capacity also appropriate for storing CO_2 captured in Thermal power plant Šoštanj.

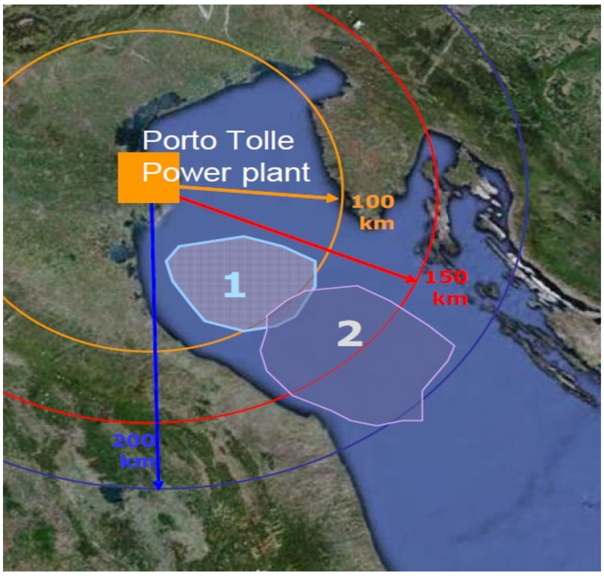

Figure 7: Promising Adriatic offshore storage capacity

3. ECONOMICAL EVALUATION OF RETROFITTING THE CC TECHNOLOGY TO UNIT 6 OF THE THERMAL POWER PLANT ŠOŠTANJ

Retrofitting carbon capture technology to pulverized coal combustion boilers like Unit 6 in Power plant Šoštanj requires additional energy necessary to carry out the capture and compression process. It also creates additional cost due to:

- capture and compression investment cost,
- operation and maintenance cost,
- transportation cost and
- storage cost.

In case of Unit 6 all of them are estimated in next sections.

3.1 Capture and compression cost

Capture and compression cost consists of

- investment cost and
- operation and maintenance cost.

The investment cost depends on the size of the equipment and the concentration of CO_2 in the flue gas. Carbon dioxide capture adds 44-87 % to the capital cost of the reference plant, while achieving CO_2 reductions of approximately 80-90 %. Capture and compression investment cost is in range between 561 and 835 €/kW. The representative value is 620 €/kW.

Capture and compression representative investment cost of Unit 6 with installed capacity 600 MW is 372 Mio. €. The cost varies from 336 to 501 Mio. €.

The operation and maintenance cost consists of labor costs and material costs (solvent and additives consumption, disposal of spend materials). For chemical absorption unit fixed operational and maintenance costs is estimated at 4 % of the initial investment cost. In addition variable operational and maintenance cost factor can be used. It takes the operational time into account. Default factor for variable operational and maintenance cost is 4 % for coal fired power plants.

In the case of Unit 6 8 % of investment cost is taken to calculate annual fixed and variable operational and maintenance cost. Taking into account representative investment cost total annual operational and maintenance cost is 30 Mio. €. In case of low investment cost operational and maintenance cost is 27 and in case of most expensive carbon capture and compression equipment this cost is 40 Mio. € per year.

Carbon capture and compression investment cost together with operational and maintenance cost per MWh of electricity generated by Unit 6 is in range from 20,8 €/MWh to 31,1 €/MWh. The expected representative value is 23,0 €/MWh. When cost arising from loss of electricity generation is taken into account carbon capture and compression cost together with operational and maintenance cost is in range from 28,2 to 42,0 €/MWh. The representative value is 31,1 €/MWh.

3.2 Transportation costs

Transport is the stage of CCS technology that links sources and storage sites. It is covered by the regulatory framework concerned for public safety that governs pipelines and shipping.

In the context of long distance movement of large quantities of carbon dioxide, pipeline transport is part of current practice. Pipelines routinely carry large volumes of different gases and liquids over distances of thousands of kilometers, both on land and in the sea.

The costs of pipelines can be categorized into three items:

- construction costs:
  - material/equipment costs (pipe, pipe coating, cathodic protection, telecommunication equipment; possible booster stations);
- installation costs (labor);
- operation and maintenance costs:
  - monitoring costs,
  - maintenance costs,
  - (possible) energy costs;
- other costs (design, project management, regulatory filing fees, insurances costs, right-of-way costs, contingencies allowances).

Beside listed categories cost is also affected by the terrain. Onshore pipeline costs may increase by 50 to 100% or more when the pipeline route is congested and heavily populated. Costs also increase in mountains, in nature reserve areas, in areas with obstacles such as rivers and freeways, and in heavily urbanized areas because of accessibility to construction and additional required safety measures. Offshore pipelines generally operate at higher pressures and lower temperatures than onshore pipelines, and are often, but not always, 40 to 70% more expensive.

It should also be cheaper to collect CO_2 from several sources into a single pipeline than to transport smaller amounts separately. That is the reason that early and smaller projects will face relatively high transport costs, and therefore be sensitive to transport distance, whereas an evolution towards higher capacities (large and wide-spread application) may result in a decrease in transport costs. Implementation of a 'backbone' transport structure may facilitate access to large remote storage reservoirs, but infrastructure of this kind will require large initial upfront investment decisions. Further study is required to determine the possible advantages of such pipeline system.

In the case of ship transport the cost is comprised by many elements. Besides investments for ships, investments are required for loading and unloading facilities, intermediate storage and liquefaction units. Further costs are for operation (e.g. labor, ship fuel costs, electricity costs, harbor fees), and maintenance. An optimal use of installations and ships in the transport cycle is crucial. Extra facilities (e.g. an expanded storage requirement) have to be created to be able to anticipate on possible disruptions in the transport system.

The transportation costs for captured CO_2 on Unit 6 will be affected by all above listed categories. In the study the cost is mainly affected on the:

- distance between Unit 6 and the storage site and
- means of transport.

For the onshore as well as offshore transport costs of CO_2 captured on Unit 6 calculation are based on the literature factors. Factors take into account the amount of captured CO_2 to be transported and also the distance of transportation.

From the costs point of view it is recommended that the storage site is as close as possible to the source of CO_2. In the frame of the Geocapacity project it was found out that in Slovenia there are enough storage capacities to store captured CO_2 from Unit 6 of Power plant Šoštanj. Expected quantity of CO_2 captured on Unit 6 in the period from 2020 till 2054 amounts in range from 70,2 to 76,2 Mio.t and the representative value is 73,6 Mio.t, while the conservative estimate of storage capacity in Slovenian aquifers is 92 Mio.t CO_2.

The study differs transport costs according to:

- transport by onshore pipeline,
- transport by offshore pipeline and
- transport by ship.

The cost in the case of transport by:

- onshore pipeline is 0,008 €/(t CO_2 x km),
- offshore pipeline is 0,011 €/(t CO_2 x km) and
- by ship 0,004 €/(t CO_2 x km).

3.2.1 Transportation costs to storage sites in Slovenia

The transport of CO_2 to permanent storage sites located in Slovenia will be carried out exclusively by gas pipelines. Their exact direction will be defined within the framework of the spatial planning and environmental impact assessment. In the figure 8 the locations of storages are shown. Blue areas 1, 2, 4, 5 and 6 are locations of aquifers. Location TEŠ represents the coal mine area which is nearby Unit 6 of Thermal power plant Šoštanj and is also one of possible carbon dioxide storage sites. Number 3 marks the port Koper at the Adriatic Sea from where CO_2 can be transported by tankers.

Transportation cost depends on distance between carbon dioxide source and storage site. The closest storage site is Coal mine Velenje which is adjacent to Unit 6. It is expected that storage on this location represents the most economically feasible solution. In case of unappropriateness or unsufficiency of capacity in coal mine the storage should be done in available Slovenian aquifers.

Distances between Unit 6 of Thermal power plant Šoštanj and potentially available aquifers are in range from 15 to 110 km. In average they are around 70 km. The transport of CO_2 to permanent storage sites located in Slovenia will be carried out exclusively by gas pipeline.

Storage in Coal mine Velenje should have the cheapest transportation cost. In the study estimated transport cost to Coal mine is 0,0 €/MWh. Because this storage site is not completely investigated it is not included in further economical evaluations of retrofitting CCS.

Transport cost calculation is based on presumption, that a part of captured CO_2 could not be stored on territory of Slovenia. The average distance to storage sites in and out of Slovenia is 150 km. In that case representative transport cost without cost arising from loss of electricity generation amounts 1,1 €/MWh. The expected range is from 1,0 to 1,1 €/MWh.

In case when cost due to loss of electricity generation are taken into account representative transport cost amounts 1,3 €/MWh and the expected range is from 1,3 to 1,4 €/MWh.

Locations of Slovenian carbon dioxide storage sites are shown in figure 8.

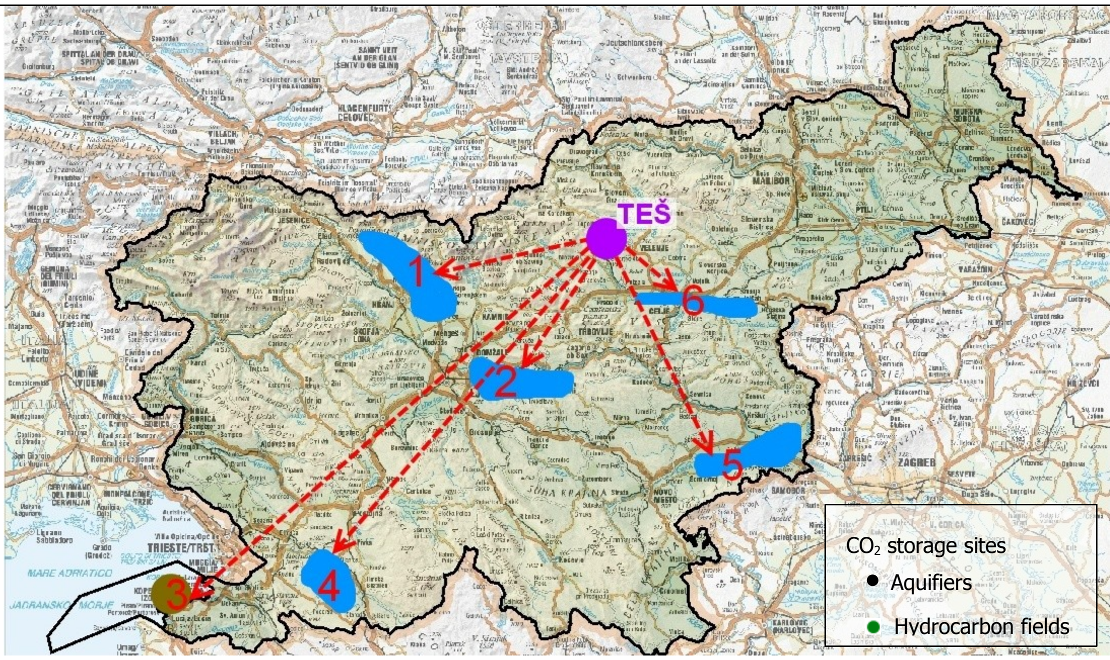

Figure 8: Locations of storage sites (1, 2, 4, 5, 6) in Slovenia and location of port Koper (3)

In case of transportation to locations out of Slovenia transport will be done by onshore and in some cases in combination with offshore pipelines. The possibility is also pipeline transport to port Koper and from there by ships to storage site in North Sea or elsewhere. The pipeline to port Koper is approximately 150 km long. The location of Koper port is shown on figure 8.

Besides Unit 6 there are some other major stationary emitters in Slovenia which can implement carbon capture technology too. Three of them are shown on the figure 9. On the same figure existing gas pipeline network is presented. The transmission network, designed to transport carbon dioxide, shall most probably run in the vicinity of the existing gas pipeline. Captured CO_2 from all nearby sources could be transported by the same transportation capacities and this could lower the cost of transport.

Figure 9: Gas transmission network and sources of CO_2 emissions suitable for the retrofitting the CCS technology

3.2.2 Transportation costs to storage sites in Europe

Carbon dioxide storage sites in nearby countries were checked too. In detail were examined locations that are at most 400 km from Power plant Šoštanj. They are shown on figure 10.

Large and very close storage capacities are in Croatia. On the map bellow, figure 10 are denoted by "H". The distances from source to suitable aquifers are in range from 100 to 300 km, in average 170 km.

Very close are also Hungarian storage sites. They mostly lie around 240 km from Power plant Šoštanj and are marked by "M" in the map. Unfortunately they are not very abundant and therefore not so suitable to store CO$_2$ captured on Unit 6 of Power plant Šoštanj.

Storage site in Austria is denoted by "A" on the map. It has a low capacity and is not suitable to be used by Unit 6 of Power plant Šoštanj.

Investigations carried out in Italy demonstrate large onshore and offshore storage capacities. On the map below, figure 10 they are marked by "I". The distances from Unit 6 to them are in the range from 250 to 350 km.

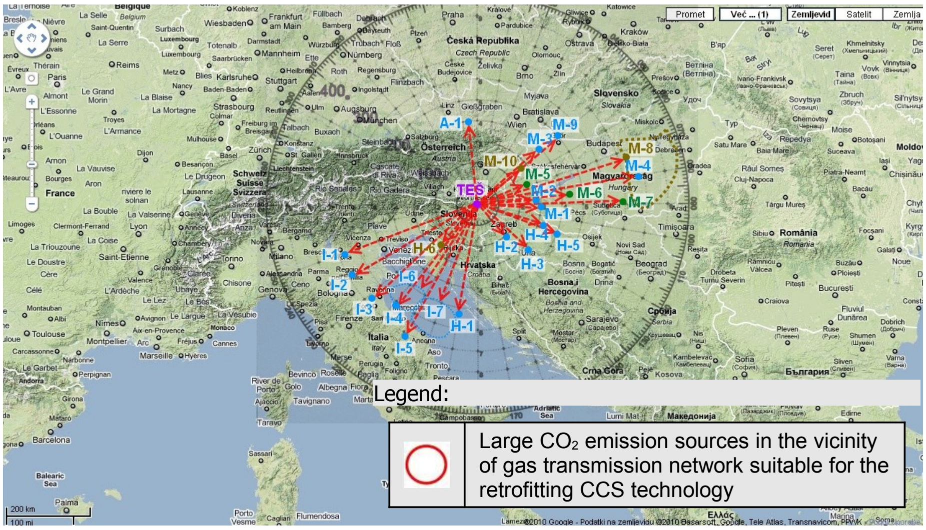

Figure 10: Locations of storage sites in Europe close to Slovenia

The transportation cost to locations out of Slovenia considers only close large capacities in Croatia and Italy.

The representative cost of transport to the storage sites 250 km from Unit 6 of Thermal power plant Šoštanj in Croatia or Italy that does not include the cost of loss of electricity production because of carbon capture operation is 1,8 €/MWh. The expected cost range is from 1,7 to 1,9 €/MWh.

The representative transport cost to the storage sites 250 km from Unit 6 of Thermal power plant Šoštanj in Croatia or Italy that include cost of loss of electricity production is 2,2 €/MWh. The expected cost range is from 2,1 to 2,3 €/MWh.

The cost of transport to Italian offshore location is higher. The most expensive is combination of pipeline transport from Unit 6 to port Koper and then by ship to North Sea.

3.3 Storage cost

The cost of storage depends on characteristics listed below:

- storage option type,
- depth and
- geological characteristics.

Further the price is affected by the number, spacing and cost of wells, as well as the facilities cost. Well and compression costs both increase with depth. Well costs depend on the specific technology, the location, the scale of the operation and local regulations. The geological characteristics of the injection formation are another major cost driver, that is, the reservoir thickness, permeability and effective radius that affect the amount and rate of CO_2 injection and therefore the number of wells needed. As some gases are corrosive and hazardous the storage cost is also affected by the composition of captured gas.

The storage costs of on Unit 6 captured CO_2 will be affected by all above listed categories. In the study the cost depends on:

- storing location:
    - onshore,
    - offshore and
- geological formation:
    - saline formation,
    - disused oil or gas fields.

Onshore as well as off shore storage costs of CO_2 captured on Unit 6 are based on the literature factors. Factors are based on the amount of CO_2 which has to be stored.

Factors show that from the cost point of view the most convenient geological formations are onshore saline aquifers and the least offshore saline aquifers. The cost to store in the disused oil or gas fields lies between the cost of onshore and offshore saline formations, but nevertheless it is closer to the cost of storing in offshore saline formations.

Storage cost takes into account next geological formations:

- onshore saline formations or coal mine:
    - representative cost is 2,2 €/t CO_2 (range from 1,5 to 4,8 €/t CO_2),
- offshore saline formation:
    - representative cost is 6,0 €/t CO_2 (range from 3,7 to 9,4 €/t CO_2),
- disused oil or gas fields:
    - representative cost is 4,7 €/t CO_2 (range from 3,0 to 6,3 €/t CO_2).

According to these costs the most convenient option is to store in onshore saline formations or in coal mine. The storage cost taken into account in case of Unit 6 is based on assumption that storage of 1 ton of CO_2 costs 2,8 €. On this basis storage cost calculated per unit of produced electricity is:

- from 2,5 as to 2,8 €/MWh in onshore saline formations in Europe including Slovenia and coal mine when cost arising from loss of electricity production is not included. Reference cost is 2,7 €/MWh.
- from 3,1 to 3,4 €/MWh in onshore saline formations in Europe including Slovenia and coal mine when cost due to loss of electricity production is included. Reference cost is 3,3 €/MWh.

Calculations are also made for cases when storage of 1 ton of CO_2 costs 1,9 or 6,2 €.

3.4 Specific carbon capture and storage cost

Evaluation of carbon capture and storage cost of Unit 6 of Power plant Šoštanj is founded on plant's technological data and appropriate capture and compression investment costs, operation and maintenance costs, transportation costs and storage costs. Included are also costs arising from loss of power production. In calculations low, high and representative values are taken. Results are expressed as cost in Euros per unit of produced electricity (€/MWh) and are presented in table 6.

Table 6: Total carbon capture and storage cost of Unit 6 or Thermal power plant Šoštanj

			Cost of loss of power production not included			**Cost of loss of power production included**		
			Min.	**Rep.**	**Max.**	**Min.**	**Rep.**	**Max**
1	Captured CO_2	(kt)	70,2	73,6	76,2	70,2	73,6	76,2
2	Investment cost	(€/MWh)	3,9	4,3	5,8	5,1	5,6	7,6
3	Operational cost	(€/MWh)	4,9	5,4	7,2	6,4	7,1	9,5
4	Maintenance cost	(€/MWh)	7,5	8,3	11,2	9,9	10,9	14,7
5	Storage cost (1,9 €/tCO_2)	(€/MWh)	1,3	1,4	1,4	1,7	1,8	1,9
6	Storage cost (2,8 €/tCO_2)	(€/MWh)	1,9	2,0	2,1	2,5	2,7	2,8
7	Storage cost (6,2 €/tCO_2)	(€/MWh)	4,3	4,5	4,6	5,6	5,9	6,1
8	Transport (In Slovenia 150 km)	(€/MWh)	0,8	0,8	0,9	1,0	1,1	1,1
9	Transport (Abroad 250 km)	(€/MWh)	1,3	1,4	1,4	1,7	1,8	1,9
	TOTAL - (2+3+4+6+8)	**(€/MWh)**	**21,3**	**23,3**	**29,7**	**28,1**	**30,6**	**39,1**
	TOTAL - (2+3+4+6+9)	**(€/MWh)**	**21,9**	**23,8**	**30,3**	**28,8**	**31,4**	**39,9**

Retrofitting carbon capture and storage to Unit 6 of Thermal power plant Šoštanj induces cost in range from 21,3 to 29,7 €/MWh when storing is being carried out on the territory of Slovenia. Reference cost in this case with no additional cost arising from loss of electricity generation and at carbon dioxide storage cost 6,2 €/tCO_2 is 23,3 €/MWh. Taking into account cost that originates from energy transformation efficiency loss due to CCS process energy needs cost of carbon capture and storage is in range between 28,1 and 39,1 €/MWh while reference cost is 30,6 €/MWh.

Transport to locations out of Slovenia approximately 250 km from Unit 6 rises cost to the level between 21,9 and 30,3 €/MWh. The reference value is then 23,8 €/MWh. Values don't include the increase of cost because of the loss of electricity generation. Taking into account this contribution too the cost is in the range from 28,8 to 39,9 €/MWh and the reference cost is 31,4 €/MWh.

Total carbon capture and storage cost could be even higher if the distances to storage sites are longer and the storing is more expensive.

4. CARBON CAPTURE AND STORAGE COMPARED TO EMISSION TRADING

Large combustion plants like Unit 6 of Thermal power plant Šoštanj are now integrated in European emission trading scheme. In the very next future they will have only two options to operate:

- to buy emission allowances on auctions or
- to retrofit carbon capture and storage technology and become a "zero emission" plant.

Economical evaluation of retrofitting Unit 6 of Thermal power plant Šoštanj by carbon capture and storage technology determines the level of cost that charges the electricity generation. On figure 11 a range of cost expressed by Euros per unit of electricity that originates from CCS is shown in comparison with the cost that is based on price of allowances. Lines in graph are:

- ETS determines additional cost originating from allowance's price,
- CCS_Min.+ETS shows the contribution of the lowest CCS's cost and cost of allowances that have to be bought for not captured and stored CO_2,
- CCS_Rep.+ETS represents the reference CCS's cost and cost of allowances that have to be bought for emitted CO_2 and
- CCS_Max.+ETS shows the contribution of the highest CCS's cost and cost of allowances that have to be bought for not captured and stored CO_2.

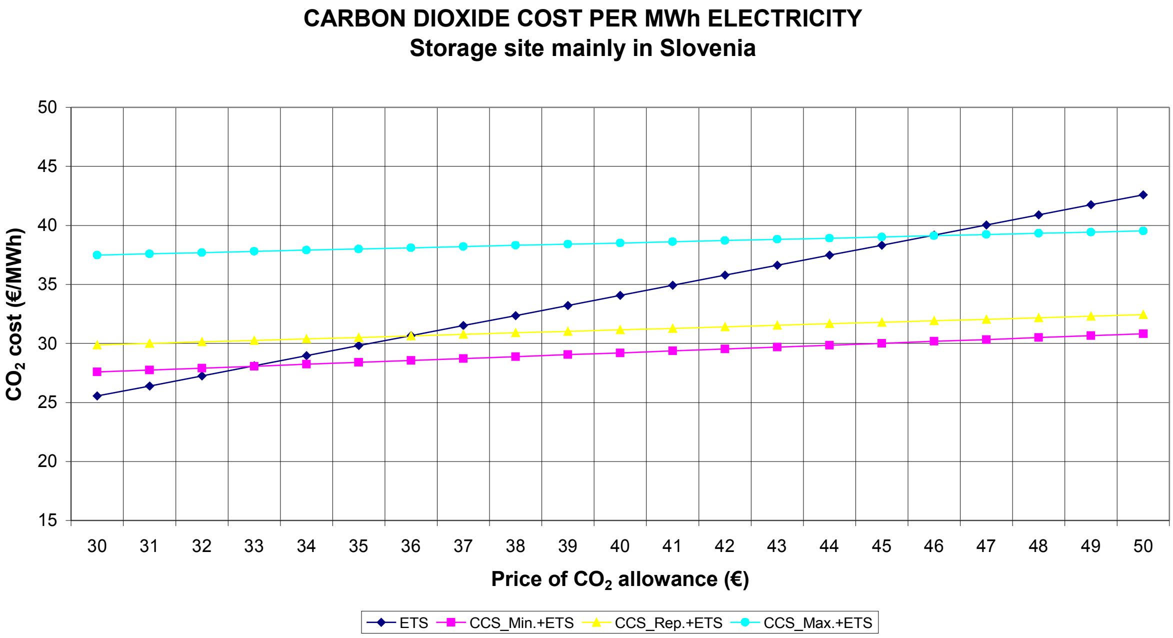

Figure 11: Carbon dioxide sequestration cost versus cost of allowances

Figure 11 exhibits that retrofitting Unit 6 of the Thermal power plant Šoštanj with carbon capture and storage equipment is economically feasible. Estimated cost is close to price of green house gas allowances. Considering the lowest CCS cost implementation of new technology is competitive with emission trading when allowance costs more than 33 €. In case of highest carbon capture and storage cost the point where CCS yields more than emission trading is at 46 € per allowance.

5. CONCLUSION

A study "CO_2 capture readiness of Unit 6 in Thermal power plant Šoštanj" prepared in June 2010 confirms that Unit 6 of Power plant Šoštanj will fulfil requirements of capture readiness defined in European legislation.

An addition to the study in greater detail analyzes availability of CO_2 storage sites in Slovenia, nearby countries and North Sea. Their availability and appropriate capacity are the condition of retrofitting CCS. In this frame onshore and offshore saline aquifers as well as depleted oil and gas fields and coal mines are examined. Above all their distance from Power plant Šoštanj and their storage capacities are checked.

It is planned that Unit 6 of the Thermal power plant Šoštanj will produce 86,6 Mio.t of CO_2 in the period from 2020 to 2054. Retrofitting CCS to Unit 6 with capture efficiency from 81 to 89 % will generate from 70,2 to 76,2 Mio.t of carbon dioxide compressed and prepared to store. Geological estimates carried out in frame of GeoCapacity project demonstrates that Slovenia has underground aquifers with total capacity about 92 Mio.t. It is sufficient to store CO_2 captured on Unit 6. Besides there is coal mine near the plant. It also represents a potential additional storage site which is under investigation. Storage sites in nearby countries like Croatia, Hungary, Austria and Italy were checked too. It was found that Croatia and Italy have large storage capacities enough to store their and other's captured carbon dioxide. Available sites are in radius of 350 km what is close enough not to make high transport cost. Another possible solution offers port Koper at the Adriatic Sea. From there it is possible to transport compressed CO_2 to suitable locations in North Sea or elsewhere by ships.

From the available storage capacities point of view Unit 6 of the Thermal power plant Šoštanj has no obstacles to retrofit carbon capture and storage technology.

In addition to the study economical parameters of retrofitting carbon capture and storage technology to Unit 6 are analyzed too. In this part investment cost, operational & maintenance cost, transport and storage cost are calculated. Cost originating from loss of power production is also considered. All of them are expressed in Euros per unit of generated electricity (€/MWh). On this evaluation is based economic feasibility of retrofitting CCS.

Investment in CO_2 capture and compression costs from 336 to 501 Mio. €. The representative price is 372 Mio. €. Annual fixed and variable operational and maintenance cost is 8 % of investment cost. From this derives that carbon capture and compression investment cost together with operational & maintenance cost per MWh of electricity generated by Unit 6 is in range from 21,4 to 31,9 €/MWh. The representative value is 23,6 €/MWh.

Transport to Coal mine Velenje near Power plant Šoštanj is the cheapest solution, but till now not completely investigated and confirmed. This possibility is not included in current economic evaluation.

Transport cost calculation to storage sites in Slovenia is based on presumption that a part of captured CO_2 has to be stored outside of the country. The average distance to potentially available onshore aquifers taken into account bridged by onshore pipeline is 150 km. In that case the representative transport cost amounts 1,1 €/MWh and the expected range is from 1,0 to 1,1 €/MWh.

When the storage sites are onshore aquifers 250 km from Unit 6 of Power plant Šoštanj for example in Croatia or Italy reached by onshore pipelines representative transport cost is 1,8 €/MWh while the expected cost range is from 1,7 to 1,9 €/MWh.

At least there is the storage cost. The cheapest is to store in onshore saline aquifers. Higher price has storage in disused oil or gas fields and the most expensive is the storage in the offshore saline formations. The cost of storing in onshore saline formations in Europe including Slovenia and coal mine are in range from 5,6 to 6,1 €/MWh. Reference cost is 5,9 €/MWh.

The sum of above costs gives the total cost of carbon capture and storage process carried out on Unit 6 of the Thermal power plant Šoštanj. When CO_2 is mainly stored in Slovenia the cost is in range from 28,1 to 39,1 €/MWh and the representative value is 30,6 €/MWh. In the case when CO_2 has to be transported to locations about 250 km from the source the cost is from 28,8 to 39,9 €/MWh and the representative cost is 31,4 €/MWh.

Total carbon capture and storage cost could be even higher if the distances to storage sites are longer, the transport is carried out by offshore pipelines or by ships and the storing is done in offshore aquifers.

The cost of electricity generation that originates from CCS is compared with the cost that is based on price of CO_2 allowances. Considering the lowest CCS cost implementation to Unit 6 of Thermal power plant Šoštanj (cheapest investment cost, storage in Slovenian onshore aquifers) is in range of cost originating from emission trading when CO_2 allowance costs more than 33 €. In case of highest carbon capture and storage cost (the highest investment cost, storage in onshore aquifers 250 km from Unit 6) the point where CCS yields more than emission trading is at 46 € per CO_2 allowance.

Addition to the study "CO_2 capture readiness of Unit 6 in Thermal power plant Šoštanj" shows that storage sites for permanent disposal of carbon dioxide captured on the new Unit 6 are available in Slovenia, Croatia and Italy. All of them are at appropriate distance, have sufficient capacity and could be reached by onshore pipelines. Cost analyzes confirm that retrofitting carbon capture and storage technology to Unit 6 of the Thermal power plant Šoštanj is economically feasible and in range with cost induced by emission trading.

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