CO_2 transport modelling, conversion and storage

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Abstract

In the context of the research project "Solar2Fuel" funded by the German Ministry of Education and Research (BMBF) (2009 – 2011) the aim is to examine the necessary steps for building up of a conversion technology of CO_2 into a valuable product with the help of solar energy. In focus of this article is the photocatalytic conversion of carbon dioxide to methanol (CH_3OH), the identification of large-scale solar regions in South Europe and North Africa and the CO_2 transport via pipeline. The estimated scenarios are built on a calculated CO_2 amount of 50 Mt/a which is the equivalent to ten modern coal fired power stations with an installed power of 800 MW each.
Keywords: photocatalytic, CO_2 transport, CO_2 pipeline, CO_2 conversion, solar areas.

1 Introduction

Solar2Fuel is a joint project between EnBW Energie Baden-Württemberg AG, BASF SE, University of Heidelberg and Karlsruhe Institute of Technology (KIT). The project is coordinated by the association of German Engineers e.V. (VDI). The aim of the entire project is the development of a novel technology for the chemical conversion of CO_2 into a useful product with help of sun energy. In focus is the methanol recovery as a fuel e.g. usage in combustion engines or fuel cells. Recycling of CO_2 from stationary resources can serve as an important contribution for a sustainable energy economy as well as the prevention of climate change from CO_2 emissions.

WIT Transactions on Ecology and the Environment, Vol 143, © 2011 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/ESUS110401

The entire process chain starts right from the supply of liquefied CO_2 from the power stations with CCS-technology (CCS = Carbon Capture and Storage) with the following steps:

1. Transport modelling from Germany to Northern Africa via CO_2-pipeline
2. Injection of CO_2 into the reactor field and conversion to methanol with solar irradiation
3. Storage of CO_2 during the night and in sun free hours
4. Back transport of the gained fuel

This article mainly concentrates on points 1) and 2)

2 Photocatalytic conversion of carbon dioxide to methanol – viability check

CO_2 from stationary sources, which was separated from the flue gas, liquefied and transported in a pipeline to a region with high solar irradiation, shall be catalytically converted together with water to methanol by use of solar energy after eqn (1):

$$CO_2 + 2H_2O \xrightarrow{h*\upsilon} CH_3OH + \frac{3}{2}O_2 \tag{1}$$

For this purpose a catalyst shall be developed that converts CO_2 in aqueous solution into methanol via sunlight in a photocatalytic reactor. The reactor is fed with water and CO_2 only. Methanol will accumulate as a low concentrated mixture with water.

The reactor needs to collect solar energy over a huge surface area to supply enough energy for the CO_2 conversion and is defined as “aperture area”. The set boundary conditions are to convert 50 Mt CO_2/a. Moreover, the cost of the resource CO_2 is estimated as well as the revenues from the sales of the product methanol.

Since the reactor is still to be developed, the investment and operating costs are unknown: Therefore the analysis can only be realised by reverse the gap of knowledge in setting the certain basics for the CO_2 conversion, i.e. price per tonne CO_2, efficiencies of the conversion process, etc. The percentage of CO_2, supplied to the reactor that is converted to methanol is described as “CO_2 conversion efficiency”. In the economic calculations the assumption is made that 90% of the CO_2 can be converted into methanol and called the conversion efficiency.

Next to the CO_2 conversion efficiency, the reactor has an efficiency in terms of percentage solar energy converted to chemical bound energy as methanol, defined as “reactor efficiency”. For example, an efficiency of 4% means, that a solar irradiation of 2000 kWh/m²/a gives rise to 80 kWh methanol in higher heating value (which is 6.3 kWh/kg). Thus 12.7 kg/m²/a or 127 t/ha*a methanol could theoretically be produced.

The monetary value of methanol will strongly influence the revenues and is assumed to a current price scenario of 250 €/t. This is equivalent to the free on board (FOB) price of methanol in the harbour of Rotterdam (RDAM) in the Netherlands during the past twelve month, published by INEOS Paraform [2]. In a high price scenario, 400 €/t of methanol is assumed.

In the following section, the specific CO_2 costs per ton methanol and in turn, the rest budget per ton methanol after deduction of CO_2 cost are evaluated with a CO_2 supply cost of 50 €/t CO_2. Under stoichiometric conditions, 1.375 kg CO_2 is consumed to yield 1.0 kg methanol (which relates to conversion of 100%). With 50 Mt CO_2 of this corresponds to 32.7 Mt methanol. With decreasing CO_2 conversion efficiency the supplied amount CO_2 per ton methanol increases.

In case of lower CO_2 conversion efficiencies, specific CO_2 cost per metric ton methanol is strongly increasing (Figure 1). With 90% CO_2 conversion efficiency CO_2 cost would be 76 €/t methanol; with 17% and 27% CO_2 conversion efficiency, CO_2 cost per ton methanol would be as high as the market value of methanol in the harbour in Rotterdam and in the high methanol price scenario, respectively. Since the reactor investment, the operating costs and the product purification are not considered, significantly higher CO_2 conversion efficiency than the 17% and 27% threshold is crucial in an economic perspective.

Figure 2 shows the remaining budget of the revenues per ton methanol after deduction of CO_2 supply cost (50 €/t) depending on CO_2 conversion efficiency.

In the most optimistic considered case of 90% CO_2 conversion efficiency, the remaining budget can reach up to 174 €/t methanol in the current and 324 €/t in the high methanol price scenario.

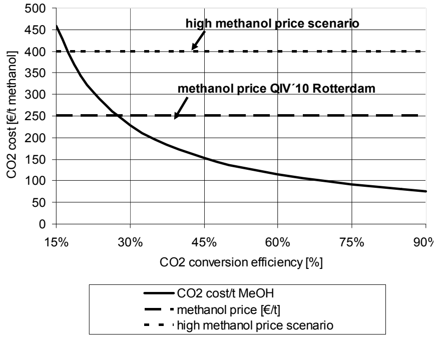

Figure 1: CO_2 cost per metric ton methanol dependent on CO_2 conversion efficiency in the photocatalytic reactor, CO_2 supply cost set to 50 €/t.

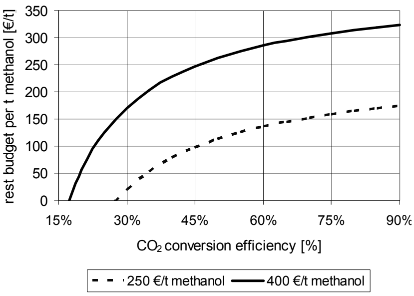

Figure 2: Remaining budget of the revenues per ton methanol after deduction of CO_2 supply cost for the current and high methanol price scenario.

In the following, the necessary reactor aperture area to convert 50 million tons CO_2 per year is examined. The required area depends on the efficiency of the photocatalytic reactor as well as the solar irradiation. Figure 3 pictures the aperture area for solar irradiation of 1000 kWh/m²/a, 1500 kWh/m²/a, 2000 kWh/m²/a as well as 2400 kWh/m²/a in case of 90% CO_2 conversion efficiency for a range of 2%-20% reactor efficiency.

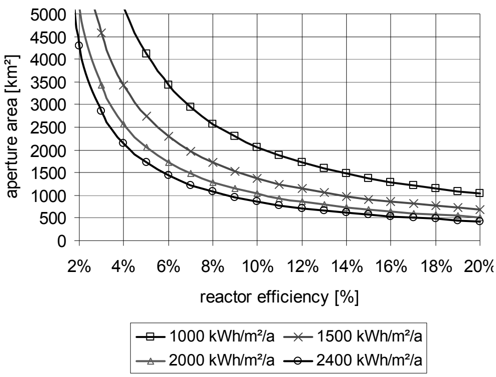

Figure 3: Aperture area to convert 50 million metric tons of CO_2 per year depending on solar irradiation of 1000-2400 kWh/m²/a as well as the reactor efficiency varied from 2-20% and a CO_2 conversion efficiency of 90%.

3 Transport of CO_2

Most conducted CCS studies have been mainly focused on the capturing part of the CCS chain and little on the transportation links in the chain. A transportation infrastructure that carries CO_2 the necessary quantities will require a large network of pipelines and possibly in combination with tankers.

The CO_2 emissions of German power plant facilities average at over 370 Mt per year. Beginning from 2012 the EnBW coal-fired power station in Karlsruhe (RDK 8) will account for an additional 5 Mt of CO_2. With the background of the European CCS regulation a new infrastructure will be needed to enable transportation of big amounts of CO_2 in future. In the following the pipeline transportation as being most viable is considered.

The transportation costs vary between 1 and 3.5 million € per kilometre depending on factors, such as:

- Construction planning
- Distance and topography
- Material costs and costs for protection against corrosion
- Energy costs
- Right-of-way costs
- Monitoring costs

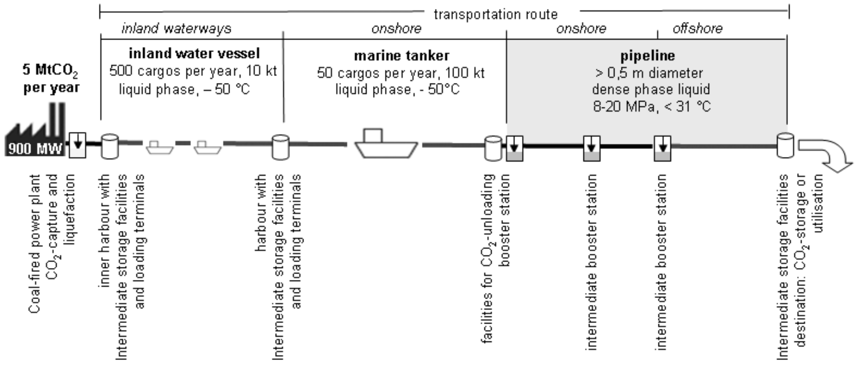

Figure 4: Options to transport 5 Mt CO_2 per year.

The transportation capacities of pipelines with large inner diameter (> 1100 mm) reach far above 50 Mt CO_2 per year. The CO_2 transport is possible in pipelines under high pressure (8–20 MPa) usually in dense liquid phases. A high energy investment is attached for a successful gas conditioning before and during the transport. Table 1 shows alternative transport means, such as ship, trains and trucks – applicable for smaller amounts of CO_2.

Table 1: Means of CO_2-transport and capacity.

Infrastructure for CO_2-transport	**Amount of CO_2 to be transported**	**Pressure and temperature conditions [3]**
Pipeline	As a function of the pipeline diameter > 20 Mt /a	Normal temperature < 31.4°C very high pressure 8 – 20 MPa
marine tanker	up to max. 100000 t /cargo	Low temperature -55 to -50°C high pressure 0.6-0.7 MPa
train	1000 – 3000 t /cargo	Low temperature -20°C high pressure 2 MPa
Truck	20 t /cargo	Low temperature -20°C high pressure 2 MPa

3.1 Pipeline route

The destination of the pipeline in the model is exemplarily the CCS area In-Salah in Algeria. In-Salah is used as target destination due to the high potential of available land for solar irradiation and the potential of CO_2 storage in direct neighbourhood to existing gas fields. The selected routes are oriented along existing or planned pipelines of the European natural gas network. The analysed transport routes from Germany to In-Salah in Algeria range from 2700 to 3750 km. A theoretical CO_2-Pipeline would cross the Mediterranean (Figures 5 and 6).

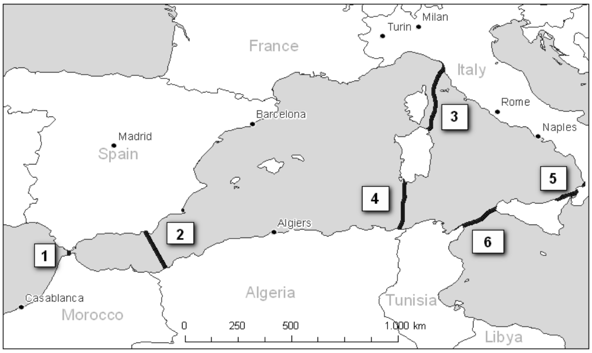

Figure 5: Pipeline routes to cross the Mediterranean Sea.

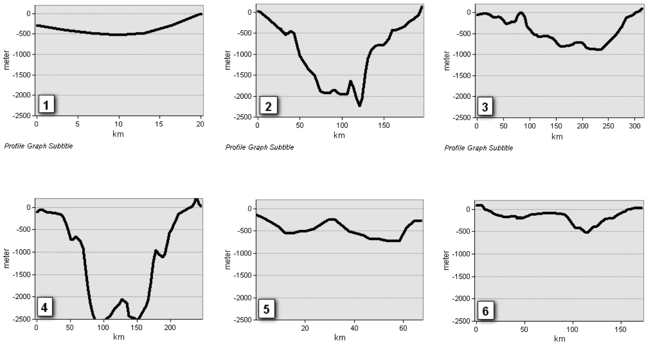

Figure 6: Elevation profiles [5] for different offshore-routes to cross the Mediterranean Sea.

3.2 Simulation and calculation of CO_2-pipelines

The costs of a 3000 km CO_2-Pipeline to transport large quantities of CO_2 (50 Mt/a) over the Alps and the Mediterranean Sea is calculated using a program for stationary and dynamic calculation of utility networks STANET® [8].

Model input:

- Length of the pipeline transportation routes and terrain profile
- CO_2-Capacity per year 50 Mt CO_2
- Operating pressure minimum 8 MPa, maximum 20 MPa
- Onshore: Costs for civil engineering
- Offshore: costs for pipelay vessels per day: 250.000 €; 1 km of pipeline can be laid per day
- Steel price, i.e. 600 €/t
- Costs for corrosion protection, i.e. 100 €/m
- Electricity rate, i.e. 0.05 €/kWh.

Model output:

- Pipeline diameter and wall thickness
- Expected pressure loss and required number of pumping stations
- Energy demand per tonne CO_2 all along the pipeline distance
- Estimation of construction and operating costs (pipeline and pumping stations)

With the set boundaries the costs of the construction of 3000 km pipeline are estimated from 5.9 billion € for a diameter of 1100 mm to 7.5 billion € for a diameter of 1400 mm. Furthermore there are costs for planning, approval processes, monitoring systems, special constructions such as tunnels and culverts etc. The modelling of a mass flow of 50 Mt of CO_2 per year and a pressure between 8 and 20 MPa shows that 3 to 8 compressor stations respectively for a diameter of 1400 mm and 1100 mm would be required to realise the entire route. The operating costs per year are estimated about 44 million € (Table 2) not considering the liquefaction of CO_2 (large investment and operating costs necessary).

Table 2: Cost estimation of the pipeline modelling (capacity 50 Mt CO_2/a, length 2965 km, diameter 1100 mm).

Pipeline construction	**Investment costs (*) million €**	**Operating costs million € per year**
Pipe laying	1738	
Pipe manufacturing (2965 km)	4071	
anti-corrosion layer	4	0.60
section gate valve	27	
Compressor stations (#8)	66	43
Control system	30	0.40
Total	**5936**	**44**

(*) The investment costs in Table 2 for planning, approval processes, monitoring systems, special constructions such as tunnels and culverts are not included.

With the total investment and operating costs of Table 2, the specific transportation costs for one ton CO_2 is calculated with net present value method. The cost per ton CO_2 does strongly depend on the load factor of the pipeline. The maximum annual capacity is 50 Mt. If parts of the CCS power plants do not run, the full pipeline capacity will not be utilized. Thus, the annual transported amount of CO_2 can be lower than 50 Mt. This aspect is considered in calculating the specific transportation cost by varying the pipeline load factor between 70% and 100%.

The depreciation period is set to 35 years which is the usual period taken for large investments (e.g. power stations). Three cases of interest rate are considered: 8%, 10% and 12%. Figure 7 shows, that the specific transportation cost from Karlsruhe to Algeria can be 10 to 14 €/t CO_2 with high pipeline load factor and 8% to 12% interest rate, respectively.

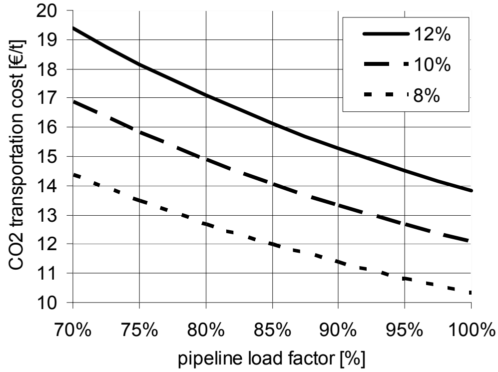

Figure 7: Specific transportation cost per ton CO_2 from Karlsruhe to In-Salah in Algeria depending on the pipeline load factor for different interest rates.

4 CO_2 -storage in porous sedimentary strata

Alternative to the CO_2-conversion permanent storage of CO_2 in porous sedimentary strata - as the last stage of the CCS chain - has been assessed due to the fact that the CO_2 flow will be on 8760 h the year but the solar irradiation only be available over certain unpredictable hours over the day. The storage capacity is very uncertain to estimate and depends on porosity and permeability values as well as pressure and temperature conditions in the deep subsurface (between 800 and 2500 m [7]). Assuming a porosity of 10% one m^3 of sedimentary rock is able to absorb a theoretical amount of 20-90 kg CO_2. The major geological necessity is a thick impermeable layer in the roof. When selecting CO_2 storages sites, ownership conflicts and competitive uses with deep geothermal energy, compressed natural gas storage and the use of groundwater should be avoided.

5 Identification of large-scale solar regions

For the identification of large-scale solar regions in southern Europe and northern Africa it was calculated in Chapter 2 that at least 1300 km² of area is needed to place solar reactors with 8% reactor efficiency. The analyses of regions was concentrated in Europe beyond the border of 1500 kWh/a/m² and further increased on the African continent. Especially the collecting of the necessary homogenous land use data over the study area and the adjacent processing was very complex. These regions are potentially suitable for large area usage of solar energy facilities. In the context of the research project, these areas are analysed for the potential building of photo-chemical reactors used possibly for the conversion of CO_2. The necessary systems are not available yet (Chapter 2).

The identification of potential areas works in an iterative mode and is performed in a Geographical Information System (GIS) environment.

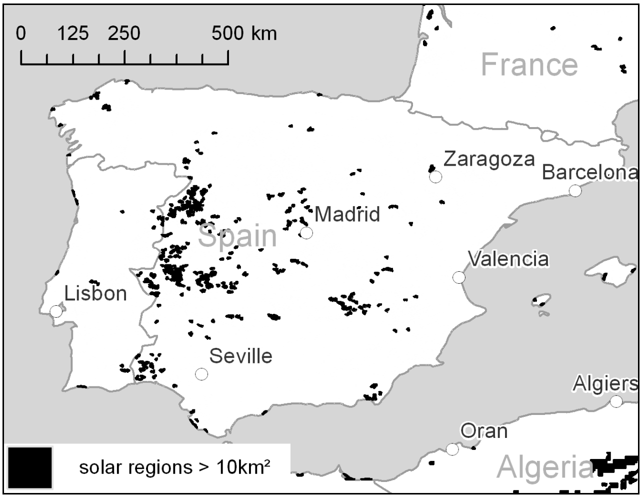

Figure 8: Identification of large-scale solar regions in Spain and Portugal by summation of restriction areas (inland waters, urban areas, forests, protected areas, agricultural areas, mountainous area).

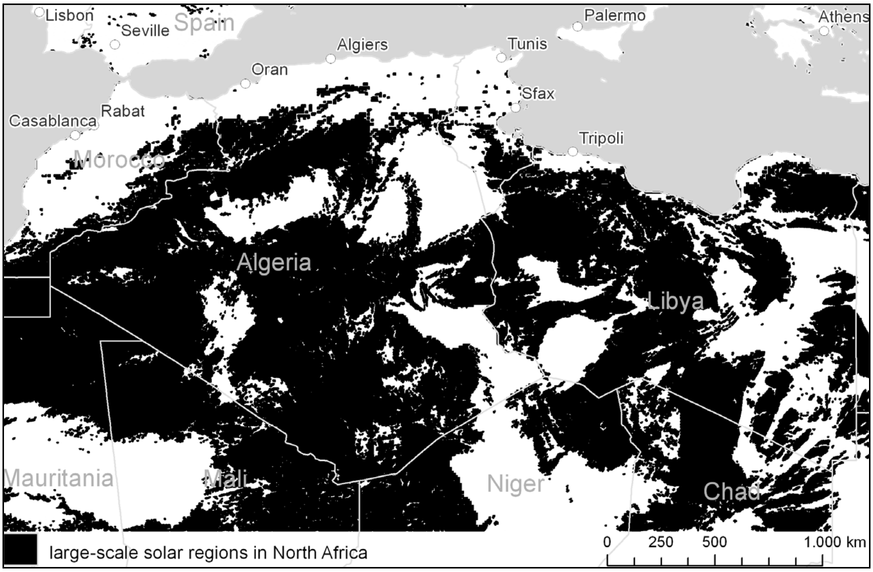

Figure 9: Identification of large-scale solar regions in North Africa by summation of restriction areas (inland waters, urban areas, forests, protected areas, agricultural areas, mountainous area, salt marshes and sand dunes).

The following inputs/exclusions are set: Yearly mean of solar irradiation [6], urban areas [1, 9], inland waters [1, 9], forests [1, 9], agricultural areas [1, 9], protected areas [4, 10], mountain slope [5]. Figure 8 shows the GIS results and the limitations of large associated areas in the example study of Spain with a maximum of 500 km^2. However when focussing on North-Africa continent, Figure 9 shows that large and homogenous areas are available with a potential of high solar irradiation.

The remaining dark areas in Figures 8 and are the ones which are potentially available for solar usage.

6 Conclusion

In this paper, it was examined the investment and operating costs for a 50 Mt annual capacity CO_2 pipeline from Karlsruhe, Germany, to In-Salah, Algeria. It was calculated, that the construction costs of the pipeline are around 5.9 billion € and the specific transportation cost inclusive the operating costs can be within a cost range of 10 to 14 € per ton if the pipeline operates at full capacity. Taken the cost of 30-40 €/t for CO_2 capturing and liquefaction at the power plant into account [7], CO_2 from Germany can be supplied in Algeria for roughly 50 €/t.

The costs and the dimensioning of the calculated pipeline routes for the CO_2 transport are already well estimated. However not examined yet are the social acceptances of such a trans-national project. Further and detailed work will be started in 2011 with a pipeline planning study in Germany from the capture site to the potential geological storage site. The limitations from the planning to the construction and realization will be examined in detail.

Together with the remaining budget per ton methanol from Figure 2, the allowed investment for the reactor field inclusive the operating costs is estimated with the net present value method. The value creation of the solar driven CO_2 conversion of methanol was evaluated, using today's market price of methanol in the harbour of Rotterdam. The budget to finance the infrastructure and operating costs for 50 Mt CO_2 conversion over a 35 year time period was calculated with 10% interest rate. The produced amount of methanol is again a function of the pipeline load factor. With a lower load factor, less methanol can be produced. Figure 10 shows the resulting cash value is 40 to 55 billion € in case of the current methanol price scenario (remaining budget after deduction of CO_2 cost 174 €/t). In the high price scenario (400 €/t methanol, 324 € remaining budget) the cash value is between 70 and 100 billion €. This amount is the maximum allowed invest into the reactor field inclusive the operating costs during the 35 years depreciation time (Figure 10).

The necessary surface area for the solar CO_2 conversion was estimated. In case of high annual solar irradiation of 2000 $kWh/m^2/a$, about 1300 km^2 are required to convert 50 Mt CO_2 per year in case of a reactor efficiency of 8%.

In Spain such extensive and connected large areas could not be identified. However the analysis of Algeria shows that there are potential large, flat and sparsely populated areas with a high and continuous solar irradiation up to 2400 $kWh/a/m^2$.

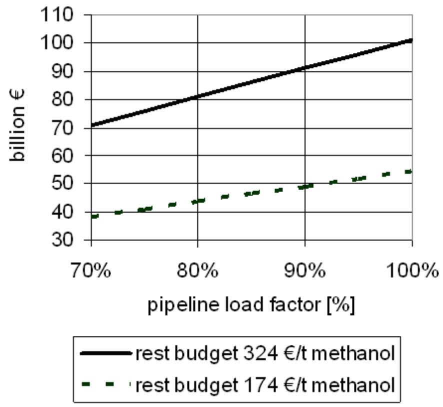

Figure 10: Cash value of the photocatalytic reactor field depending on the pipeline load factor, 35 years depreciation period and 10% interest rate.

The promising CO_2 conversion – theoretically described in Chapter 2 – will need to be further developed on the laboratory scale and upscaled in a prototype application, in order to learn more about efficiency, dimensions and prices. This new technology will need to prove its viability in comparison to the underground CO_2 storage in depleted oil/gas fields or in porous geological formations.

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