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CO_2 Capture and Storage for the iron and steel manufacturing industry: Challenges and Opportunities

M Abdul Quader, Shamsuddin Ahmed, RA Raja Ghazilla, Shameem Ahmed

Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.

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ABSTRACT

The application of Carbon Capture and Storage (CCS) in the iron and steel industry is one of the most promising options to achieve significant reduction in CO_2 emissions for the future. This paper proposes new ways to categorize the options for mitigation of CO_2 emissions and CO_2 capture. A comprehensive overview of previous CCS studies including working mechanisms, current research status, challenges and future prospects in steel manufacturing sector has been presented. The aim of this paper is to provide a network relationship map among dimension of engineering (D1), economic (D2), environmental (D3), and social (D4) and their criteria (25) of CCS technology selection by using 2-tuple DEMATEL method. Results shows that to develop cost competitive and energy efficient CO_2 capture methods and processes can be big challenges in the iron and steel manufacturing sector, while a lot of opportunities exist, such as value added CO_2 storage, industrial utilization of CO_2 and the development of the carbon trade market.

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INTRODUCTION

It is widely known that the iron and steel industry is the largest energy consuming manufacturing sector, consuming 5 % of the world's total energy consumption and producing 4-5% of the total world anthropogenic CO_2 emission. One ton of steel manufacturing emits about 1.8 tons of CO_2 (Patel and Seetharaman 2013) and collective energy demand of steel production is 21.0–35.4 GJ/t steel (Burchart-Korol 2013). More importantly, steel manufacturing industry contributes the biggest share of around 27% CO_2 emission of the global manufacturing sectors (Mandil 2007).

To mitigate CO_2 emission immensely, therefore, CO_2 capture and storage (CCS) is considered one of the most promising options to achieve significant reduction in CO_2 emissions for the future. Iron and steelmaking industry appear as particularly suitable for carbon capture not only because of their total CO_2 emissions but also because there are many industrial processes that generate gas streams rich in CO_2, or in some cases pure CO_2 from single fixed and easily accessible points . It might enable for CCS at low energy penalty and economic costs (Kuramochi, Ramírez *et al*. 2011).

Therefore, projects for reducing CO_2 emissions in the iron and steel industry around the globe in many countries are primarily focused on the iron-making process; ULCOS (Ultra Low CO_2 Steelmaking) project in Europe (ULCOS, 2013), COURSE50 (CO_2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50) project in Japan (COURSE50, 2013), AISI (American Iron and Steel Institute) CO_2 Breakthrough Program in the USA (Steel Recycling Institute, 2013), and CO_2 Breakthrough Framework of POSCO in Republic of Korea (POSCO, 2013). Among these, the EU ULCOS program is the most comprehensive and ambitious program.

In this paper we critically analyzed the previous studies of CCS in iron and steel industry with different ways of CO_2 mitigation. We evaluated the different dimension and their criteria of CO_2 capture, utilization, transportation, and storage by using DEMATEL method. Finally, this study concludes with few key challenges of CCS development and deployment in iron and steel industry and future research outlook. This paper, hopefully, will be useful for engineers, researchers, steel companies, policy makers, investors and other interested parties to build sustainable green iron and steel industry.

1. *Sources of CO_2 emission in iron and steel industry:*

An Integrated Iron and Steel Mill (ISM) consists of a number of complex series of interconnected plants, where emissions comes out from many sources (10 or more) (Birat and Maizière-lès-Metz 2010). Huge amount

Corresponding Author: M Abdul Quader, Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.
Tel: 603-7967 4455; Fax: 603-7967 5317; E-mail: maquader.me@gmail.com

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of CO_2 is produced by the reduction reaction in the blast furnace and the combustion reaction of carbonaceous materials (coke breeze, etc.) and carbon-containing gases, such as blast furnace gas (B gas) and coke oven gas (C gas) in the sintering machine, coke ovens, and hot stoves (SATO, YAMAMOTO *et al.*). Thus, Iron oxides are chemically transformed into molten iron (Fe) emitting massive amount of CO_2 and carbon monoxide (CO) as a by-product gas or blast furnace gas (BFG). The main reactions ironmaking processes are listed as following equations:

$C + ½\ O_2 \rightarrow CO$

$Fe_2O_3+3CO \rightarrow 2Fe+3CO_2$

$C+O_2 \rightarrow CO_2$

$CnHm+ (n+m/4)\ O_2 \rightarrow nCO_2+ (m/2)\ H_2O$

A CO_2 emission profile of a typical BF/BOF integrated steel plant has been presented in Fig.5. (Hasanbeigi, Arens *et al.* 2014).

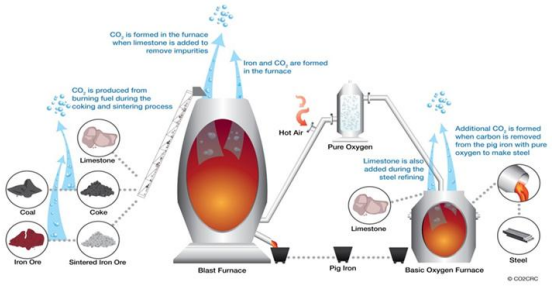


Fig. 1: CO2 emissions from a typical iron and steel industry (JP. Birat 2010).

The main process units at iron and steel production where raw materials combination with fuel combustion, contribute to CO_2 emissions including pellet/sinter plant, non-recovery coke oven battery combustion stack, coke pushing, BF exhaust, BOF exhaust, and EAF exhaust [34].

3. Ways to mitigate CO_2 emissions:

Based on the sequences of CO_2 emissions from iron and steelmaking processes into the atmosphere, the ways of CO_2 mitigation can be divided into three categories: (1) carbon source based, (2) carbon emitted minimization based and (3) carbon sink based

The idea of carbon source based mitigation is to substitute carbon based fuels. The CO_2 can be prevented from emitting by using "free-carbon" (or "less carbon") energy carriers instead of fossil fuels. The energy of the earth primarily comes from the solar energy. In other words, the solar energy is the only energy source, while all others are energy carriers, like the fossil fuels, the wind energy, the nuclear energy, the water power, the biomass, the fuel cells, and so on. By switching the energy carriers from fossil fuels to others, the demands of energy consumption can be met with less CO_2 emissions.

The second category is to minimize CO_2 emitted from steel plants by energy saving. This means fewer fossil fuels will be consumed to meet the energy demands of human beings. As a result, less CO_2 will be emitted. This category includes the ways to improve the efficiencies of energy conversion, transportation and utilization.

The third category is based on the carbon sinks. The basic idea is, the emitted CO_2 can be restored in other carbon sinks instead of the atmosphere. A carbon cycle exists on the earth (Fu and Gundersen 2012). The atmosphere, the oceans, the lithosphere, the biosphere and the fossil fuels can be regarded as carbon sinks. The photosynthesis process is a natural process to change the carbon sinks. A similar way is called Carbon Capture and Storage (CCS).The idea of CCS is to separate CO_2 from large point sources, such as blast furnace, coke oven, sintering plant and inject it into other sinks, like the oceans and the lithosphere. CCS will be responsible for 19% of the world greenhouse gas reduction solution in 2050, 9% for industry and transformation and 10% for power generation (Renewables, Cities *et al.* 2012). Over 3000 CCS projects are expected to be built by 2050. The overall cost to achieve a 50% reduction in CO_2 emissions by 2050 will increase by 70% if the CCS technologies are not applied. According to (Outlook 2010), coal and natural gas will continue to be the dominant energy sources for iron and steel manufacturing in the near future. Thus, coal based steel plants are the most interesting candidates when CCS is applied to the power industry.

4. CCS studies in iron and steelmaking:

There are a few CCS development and deployment researches are going on under worldwide CO2 breakthrough programs like ULCOS, COURSE50 and etc. A number of recent techno-economic and scenario analyses (Birat , Germeshuizen and Blom 2013, Remus 2013, International Energy Agency (IEA) 2013 , Wortler 2013) shows that carbon capture and storage (CCS) in combination with a top gas recycling for the

blast furnace (TGR-BF), direct reduction (DR) with electric arc furnace (EAF), and a rather immature technology with high future potential, the iron ore electrolysis also called electrowinning (EW) are the highest long-term potential technologies for the iron and steel industry.

Table 1: key parameters of various CO2 capture options for different steelmaking processes reported in the literature.

Source of capture	CO_2 Capture technology	CO_2 Capture efficiency(%)	CO_2 captured ($MtCO_2/yr$)	Energy Consumption ($GJ/t\text{-}CO_2$)	Capture cost (€/tCO_2)	References
BFG (~23% CO_2)	Aqueous ammonia	90%		2.5 $GJ/t\text{-}CO_2$	N/A	(Han, Ahn *et al*. 2014)
Oxygen Blast Furnace (OBF)	VPSA	2.713Mt/a 84%		78.2MW/a	N/A	(Arasto, Tsupari *et al*. 2014)
Blast Furnace	PSA					
Blast Furnace	NH_3	90%				(Rhee, Kim *et al*. 2011)
Blast furnace	MEA solvent	90%	2.8		74	(Ho, Allinson *et al*. 2011)
BF	MDEA/MEA solvent	90	2.8		35	(Farla 1996)
Advanced smelting reduction	VPSA	90%			40 – 50 €/tCO2	(Kuramochi, Ramírez *et al*. 2011)
Air-blown BF	MEA MDEA Selexol Shift + selexol Advanced solvents	NA	NA	3.71-4.95 0.77 1.13-1.53 2.75	70-90 180 20-190 70	(Ho, Allinson *et al*. 2011) (J.C.M. Farla 1995) (Vlek 2007) (Vlek 2007, Ho, Allinson *et al*. 2011) (Tobiesen, Svendsen *et al*. 2007)
TGRBF	MEA,VPSA, Selexol Membrane Membranes, VPSA, MEA	90 80-97 90	3.35 Variable Variable	3.92	€23-37 €15-17 €26-64	(Torp 2005) (Lie, Vassbotn *et al*. 2007) (Duc, Chauvy *et al*. 2007) (Kuramochi, Ramírez *et al*. 2011)
COREX	MEA solvent Selexol Shift + selexol Membrane	90 90	2.0 Not stated	4.85 Not stated 1.23	56 40 20-110	(Ho, Allinson *et al*. 2011) (Torp 2007, K. Lampert 2010) (Gielen 2003)
Advanced smelting reduction	Purification only	NA	NA	NA	NA	(Birat 2006)
Onsite power plant & blast stoves	MEA, new solvents	90	1.9-2.4	NA	€55-85	(Tsupari, Kärki *et al*. 2013)

However, according to (Morfeldt, Nijs *et al*. 2014) and (Fischedick, Marzinkowski *et al*. 2014) analysis, hydrogen based steelmaking would be a major technology option for production from virgin materials as wells as economically attractive in the second half of the current century due to the risings price of coal and CO_2 allowances. But to meet the target 80% reduction of CO_2 emission within 2050, development and deployment of CCS technology would be the prime solution.

3. *CO2 Separation/capture options:*

It is estimated that the capture stage could account for 70–90% of the totaling operating costs of a CCS system (Patel and Mutha 2004). Due to this high cost percentage much research has been conducted in the area of CO_2 capture. Currently, CO_2 capture technology can be divided into four categories, each of which requires a distinctly different approach to CO_2 capture (Spigarelli and Kawatra 2013). The four categories are:

1. Post-combustion: capture of CO_2 from flue gases created during fuel combustion with air.
2. Pre-combustion: capture of CO_2 from a synthesis gas before fuel combustion.
3. Oxy-combustion: capture of CO_2 from flue gases created during fuel combustion with oxygen.
4. Chemical looping combustion: capture of CO_2 from flue gases created during combustion with oxygen transported via a metal oxide.

The CO_2 can be separated directly from the flue gas by absorption, adsorption, membrane separation, cryogenic distillation and solidification. This is the so-called post-combustion. It is the best option for iron and steel industry. Fig. 2 shows different CO_2 capture technologies.

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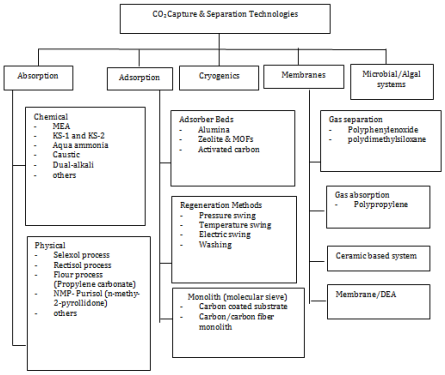


Fig. 2: Various CO_2 capture technologies.

Selecting proper methods for capturing CO_2 depends on the flue gas conditions, the concentration and pressure. Higher CO_2 concentration leads higher CO_2 recovery ratio. It is usual to employ the chemical absorption method if the CO_2 concentration in feed stream is relatively low and the feed gas stream is at atmospheric pressure. One can observe that for the case of BFG, the best option lies in the border line of absorption and adsorption techniques as shows in Fig.3.

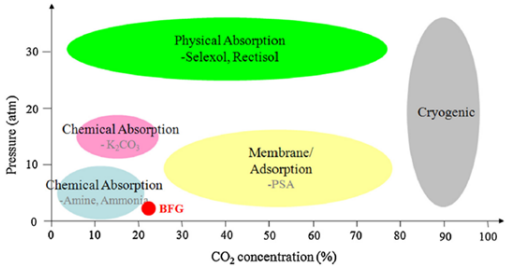


Fig. 3: Technical option for CO_2 capture depending on the feed pressure and CO2 concentration

Table 2: Performance and energy requirements for a range of mature CO_2 capture technologies for the Steel Industry (Hooey, Tobiesen et al. 2013, Romano, Anantharaman *et al*. 2013, Rootzén and Johnsson 2013, Saima, Mogi *et al*. 2013).

	Units	PSA	VPSA	VPSA+ compression and cryogenic flash	Amines + compression	PSA + cryogenic distillation compression
Recycled gas (process gas)						
CO yield	%	88,0	904	973	999	100
CO	% vol	71,4	682	689	678	695
CO_2	% vol	27	30	30	29	27
N_2	% vol	135	157	156	151	154
H_2	% vol	124	130	126	121	124
H_2O	% vol	0	0	0	21	0
CO_2 rich gas captured						
CO	%vol (dry)	121	107	33	0	0
CO_2	%vol (dry)	797	872	963	100	100
N_2	%vol (dry)	56	16	3	0	0
H_2	%vol (dry)	25	6	1	0	0
Suitable for transport and storage?		NO	NO	Yes	Yes	Yes
Energy requirements for CCS process						
Electricity consumption	KWh/tCO_2	100	105	292	170	310
Capture process	KWh/tCO_2	100	105	160	55	195
Compression for storage (110bar)	KWh/tCO_2	-	-	132	115	115
LP steam consumption	GJ/t CO_2	0	0	0	32	0
Total energy consumption	GJ/t CO_2	0.36	0.38	1.05	3.81	1.12

Table 2 shows the performance and energy requirements for a range of mature CO_2 capture technologies using in iron and steel industry.

4. CO2 utilization transportation, and storage:

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CO_2 utilization is attractive because it can offset a part of the cost of CCS development and deployment. The CO_2 can be used either directly as a working fluid or as a feedstock of chemical synthesis processes. The latter usage can be a challenge because the CO_2 is thermodynamically stable. Current examples for CO_2 utilization are urea, refrigeration systems, inert agent for food packaging, welding systems, fire extinguishers, water treatment processes, horticulture, and many other smaller-scale applications. The CO_2 can also be used for the production of organic chemicals, polymers and fuels. The industrial utilization of CO_2 can prevent the CO_2 from emitting into the atmosphere. However, the scale of CO_2 utilization is small compared to manmade CO_2 emissions, and the utilization is usually in a short term. Therefore, the industrial utilization of CO_2 is not expected to mitigate the man-made CO_2 emissions significantly.

CO_2 is commercially transported by using pipelines and ships in liquid phase where less volume is required. Generally for a short distance, pipelines are preferred and for long distances, ships are better choices for example, it can be huge expensive to construct long pipelines. Cost of transportation processes can be much lower compared to CO_2 capture processes although investment on the construction of pipelines and ships plays an important part in the total cost.

The CO_2 storage sites are regarded as carbon sinks. Two main ways exist for CO_2 storage-underground geological storage and ocean storage. The CO_2 can also be stored by mineral carbonation and industrial utilization, but the capacity is much smaller compared with the two main ways. The geological storage sites can be divided into two categories: non-value added sites and value added sites. Non-value added sites refer to those developed only for CO_2 storage, like depleted oil and gas reservoirs, deep aquifers and salt caverns. Value added sites refer to those developed primarily for enhanced recovery of fossil fuel fluids and storage of CO_2 as a secondary benefit, such as the sites for enhanced oil recovery (EOR), enhanced gas recovery (EGR) and enhanced coalbed methane recovery (ECBM). These storage options can be very attractive since the cost of CCS can be offset in this case.

5. Criteria of CO_2 capture technology selection in iron and steel industry:

In order to provide sufficient understanding of the relationships among proposed CO_2 capture and storage criteria in iron and steel industry, this chapter clearly presents the several useful dimensions and their criteria are pointed out in the literature reviews. Twenty five criteria were finally included. They belong to four main dimensions such as engineering, economic, environmental and social, as shown in Table 3.

With the purpose of evaluate the criterions of selecting CCS technologies in iron and steel industry regarding engineering, economic, environmental and social, we used 2-tuple DEMATEL method, a multi-criteria decision making (MCDM) tool.

First, to detect the relationship among the dimensions of engineering (D1), economic (D2), environmental (D3), and social (D4), the total-relation matrix T among the four dimensions is derived. Determined by experts, the result shown as Table 4 illustrates the superficial dependence and influences existing among these four dimensions and their criteria. Then, according to this total-relation matrix, the network relationship map can be constructed as a map shown in Fig.4.

6. Concluding remarks and future research:

A number of CO_2 breakthrough technologies for the drastic reduction of CO2 emissions from iron and steelmaking industry have been investigated, including (1) blast furnace with top-gas recycling (TGR-BF), (2) a new smelting reduction process (HIsarna), (3) advanced direct reduction (ULCORED) and (4) electrolysis of iron ore (ULCOWIN and ULCOLYSIS). Besides, hydrogen-based steel making and the use of biomass as reducing agent have been evaluated as supporting technology to decrease CO_2 emissions.

To develop this Breakthrough technology will take more time and deployment will take long period, if we reduce emission 80% by 2050. On the other hand, it is significant that fossil fuels are still available with cheap cost such as coal and coke, so using this fossil fuel by developing and implementing the strong CCS technology in iron and steelmaking sector would be the best solution for drastic CO_2 reduction according to IPPC plan. Few challenges are summarized by following:

- Implementation of CCS in the steel production that required a worldwide solution that would provide a level playing field- which is critical to make CCS in the iron and steel industry viable.
- Unlike power plants, where CO_2 is emitted from a single source, an integrated steel mill has multiple sources of CO_2. Emissions emitted from several stacks and occur from start to end of the iron and steel production.
- Cost competitive and energy efficient CO_2 capture methods and processes;
- Efficient, permanent and cost-effective storage; and
- Effective design and operation of CO_2 transport systems.

This research suggests further studies in order to extend the scope of this study. For example, to use of the Fuzzy topsis method for CO_2 captures technology selection and evaluation. Finally we will make the ranking of emerging steel production technologies with CCS.

Table 3: the typical evaluation criteria of CCS technology in iron and steel industry.

Dimensions	Criteria	Units	Descriptions	References
Engineering (D_1)	Safe storage (C_1) Maturity/consolidation/feasibility (C_2) Compatibility with process (C_3) Ease of technology adoption / flexibility (C_4) CO_2 removal efficiency(C_5) Energy for capture and storage (C_6) CO_2 concentration (C_7)	% GJ/t-CO_2 % (w/w)	Protect underground sources of drinking water and other natural resources (ecosystems). CO_2 capture efficiency refers to the percentage of CO_2 gas that is captured from the flue gas of an iron & steelmaking industry. Thermal energy requirement. Proper technology for capturing CO_2 depending on the flue gas conditions, concentration and pressure. Higher CO_2 concentration leads higher CO_2 recovery ratio.	(Chalmers, Gibbins *et al*. 2013) (Rhee, Kim *et al*. 2011, Yincheng, Zhenqi *et al*. 2011, Sano, Akimoto *et al*. 2013) (Sano, Akimoto *et al*. 2013) (Holling, Kandziora *et al*. 2013, Saima, Mogi *et al*. 2013, Han, Ahn *et al*. 2014)
Economic (D_2)	Investment/capital cost (C_8) Operation and maintenance (O&M) cost (C_9) Capture & storage cost (C_{10}) Fuel & Electric cost (C_{11}) Payback period/return on investment (C_{12}) Service life/plant life time (C_{13})	$ €/year €/tCO_2	O&M cost of the CO_2 capture facility is composed of steam requirement, electricity consumption for pumps and cooling tower operation, process water consumption, and chemical loss, etc. Storage cost includes all aspects of injecting and monitoring CO_2 into a geological reservoir The amount of time required for an investment to give a full return on capital costs.	(Eide, Herzog *et al*. 2013, Sano, Akimoto *et al*. 2013, Koelbl, van den Broek *et al*. 2014) (Han, Ahn *et al*. 2014) (Sano, Akimoto *et al*. 2013) (Koelbl, van den Broek *et al*. 2014) (Arasto, Tsupari *et al*. 2013)
Environmental (D_3)	CO_2 emission (C_{14}) CO/SO_2/Nx emission (C_{15}) Particles emission/Non-methane volatile organic compounds (C_{16}) Land use (C_{17}) Eutrophication Potential (EP) (C_{18}) Global Warming Potential (GWP) (C_{19})	Km^2/tCO_2 (PO_4^{3-}/t steel t CO_2/t steel	Land used over the entire lifecycle of the unit (e.g. fuel extraction, processing and delivery, construction, operation and decommissioning) A series of chemicals such as NOx, SO_2, NH3 and PO_4^{3-} and refers to the excessive supply of nutrients to soil and water. NH3 is the main eutrophication contributor caused by the degradation of the MEA medium used in the CO_2 capture process. Measure of an activity's impact on climate change, relation to carbon dioxide which has a default rating of 1.	(Burchart-Korol 2013)
Social (D_4)	Public acceptance (C_{20}) Job creation (C_{21}) Human Toxicity Potential (HTP) (C_{22}) Climate change (C_{23}) Knowledge of CCS (C_{24}) Policy, Politics &, Regulation (C_{25})	Point Person-yr/tCO_2 Years of life lost Point	Public preference for the deployment or utilization of a certain CCS technology. Human toxicity is mostly a function of flue gas emissions from ..(HF, NOx, SO_2, HCl and particulate matter all of which have a negative impact on human health "job-years" of full time employment created over the entire life cycle of the unit. Awareness and understanding of CCS by the public.	(Chalmers, Gibbins *et al*. 2013, Steeper 2013, Karayannis, Charalampides *et al*. 2014) (Burchart-Korol 2013) (Eide, Herzog *et al*. 2013) (Chalmers, Gibbins *et al*. 2013)

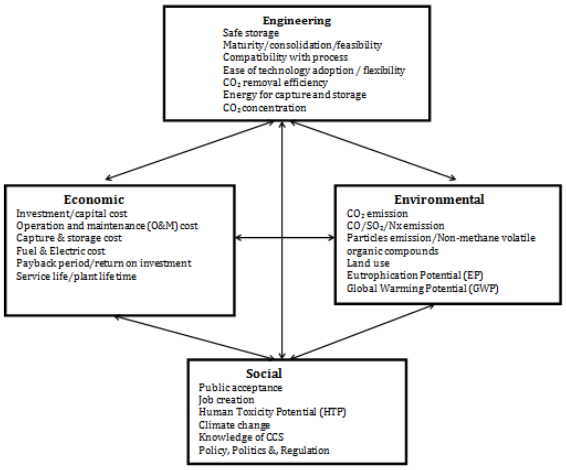


Fig. 4: Network relationship map among dimensions.

Table 4: The total-relation matrix ***T*** of four dimensions.

	D_1	D_2	D_3	D_4
D_1	1.158	1.141	1.561	1.134
D_2	0.993	0.741	1.089	0.959
D_3	1.607	1.261	1.379	1.337
D_4	1.191	1.122	1.299	0.893

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