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Best Practices for Adopting the Industrial Symbiosis Concept in the Cement Sector

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Abstract The threat of rising energy prices, increased competition for raw materials and the environmental problem of global warming, are major concerns for the European cement industry today. The challenge is to mitigate greenhouse gas emissions and to improve the energy and resource efficiency without reducing competitiveness. In this paper, a review of successful industrial symbiosis case studies in the cement industry was performed with the aim to identify the best industrial symbiosis enabling practices done worldwide. The reviewed sites are assessed based on their current symbiotic exchanges as well as their plans to extend the current industrial symbiosis activities.

Keywords: • circular economy, • industrial symbiosis • cement industry • industrial ecology • by-product synergy •

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1 Introduction

The long-term goal of the European Union's (EU) 2050 Energy Strategy is to reduce greenhouse gas (GHG) emissions by 80-95%, when compared to 1990 levels, by 2050. The low-carbon transition of the cement industry is vital for achieving this goal, as cement production accounts for 5% of global anthropogenic CO_2 emissions [1]. For instance, the production of 1 ton of Portland cement requires approximately about 1.5 tonnes of raw materials, 920-1200 kWh of thermal energy, and 100-120 kWh of electrical energy; and emits more than 0.9 ton of CO_2 [2].

Over the last decades, cement production has undergone several modifications and improvements to reduce the energy consumption and CO_2 emissions, however further reduction is still required to secure the future sustainability of this vital industry. Among different pathways to achieve CO_2 emission reduction, more and more attention has been paid to industrial symbiosis, a systems approach which aims at a win-win between environmental and economic performances through physical exchanging of waste and by-products and infrastructure sharing among co-located entities.

This paper aims to identify the best industrial symbiosis enabling practices for the cement industry, based on a review of successful industrial symbiosis case studies in the cement sector worldwide.

2 Methodology

A detailed literature search was carried out by initially selecting several keywords. Apart from cement sector related keywords, e.g. cement plant/mill, clinker, Portland cement etc., the following keywords were included: industrial symbiosis, industrial ecology, by-product synergy, eco-industrial park, and circular economy, whereby the Boolean operator "AND" was used to include several keywords in one search. No geographical limitations were applied. Search engines used included databases such as Web of Science and Scopus, as well as publisher-specific search engines such as ScienceDirect, SpringerLink, Wiley Online Library, IEEE Xplore, JSTOR, Emerald, Sage Journals, Oxford Journals etc., and freely accessible search engines, such as ResearchGate and Google Scholar.

2.1 Case study description

In total, 16 cement producer sites involved in IS activities, from 9 different countries and 4 continents, were analysed (Table 1). The majority, i.e. more than 56%, of the considered cement works are located in Asia, of which 7 reside in China as the world's largest cement consumer [3]. Among the rest of the studied cement plants 4 operate in the EU. All cement plants reside in proximity of urban areas, varying in size from 8.5 thousand (Dunbar) to 7.5 million inhabitants (Tangshan). The reviewed cement mills range from 330 thousand to 5 million tons of yearly cement production.

Table 1: Reviewed case studies

Site	Production (kt/a)	No. of IS activities	References
Aalborg (DNK)	3550	10	[4], [5]
Dunbar (UK)	1000	4	[6]
Gladstone (AUS)	1700	3	[7]
Guitang (CHN)	330	3	[8]
IJmuiden (NLD)	1400	1	[9]
Jinan (CHN)	1800	1	[10]
Kawasaki (JPN)	620	7	[11]
Kwinana (AUS)	850	6	[12]
Liuzhou (CHN)	700	1	[10]
Midlothian (USA)	900	3	[13], [14]
Pohang (KOR)	1500	3	[15]
Rizhao (CHN)	1000	3	[16]
Tangshan (CHN)	1400	1	[17]
Taranto (ITA)	900	3	[18]
Wu'an (CHN)	5000	4	[19]
Zaozhuang (CHN)	2200	3	[20]

3 Results and Discussion

3.1 Cross-sectorial synergies

Among the analysed symbiotic activities with the considered cement plants, 14 or 25% (Figure 1) involve the steel sector. In all cases expect one, i.e. in Kwinana where lime kiln dust (LKD) is being sold to the nearby pig iron plant for flue-gas desulfurization, the involved steel mills act as the donor of the shared stream. The most frequently occurring synergetic exchange is the use of blast furnace slag (BFS) and steel slag (STS) as clinker substitute for cement production, as it is present in 9 out the 16 analysed sites (Table 2). The reuse of slags from steel production does not only enhance the properties of cement, i.e. durability due to an increased setting time [21], but also has significant economic and environmental benefits, since up to 80% less energy is required than for the production of ordinary Portland cement [22]. Hence, it is not surprising that the largest documented stream exchange (Tangshan – 4 Mt/a) as well the most substantial economic advantage of 6.74 mio € (Kawasaki) in this review can be attributed to STS and BFS valorisation. BFS and STS are followed by mill scale, which is being used as an alternative iron oxide source in 14% of the IS cases involving the steel sector. There is also one document case of wastewater (WW) sludge utilisation as an alternative cement kiln fuel (Pohang).

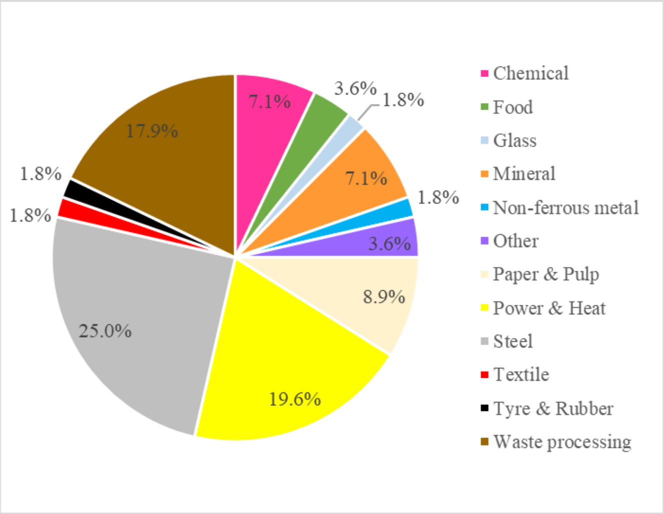

Figure 1: Sectors involved in IS activities with the reviewed cement plants

Table 2: IS activities involving the steel sector

Site	**IS activity**	**Stream**	**Magnitude**	**Benefit**
IJmuiden	Clinker substitute	BFS	1.4 Mt/a	-
Jinan	Clinker substitute	BFS	1.2 Mt/a	-
Kawasaki	Clinker substitute	BFS	315 kt/a	6.74 mio €/a
Kwinana	Desulphurization	LKD	-	-
Liuzhou	Clinker substitute	STS	1.2 Mt/a	CO_2 reduction 660 kt/a
Midlothian	Clinker substitute	STS	130 kt/a	10% production increase, 11.8 kt/a coal saved
	Alt. raw material	Mill scale	-	-
Pohang	Clinker substitute	BFS	-	-
	Clinker substitute	STS	-	-
	Alternative fuel	WW sludge	-	-
Tangshan	Clinker substitute	STS	4 Mt/a	-
Taranto	Clinker substitute	BFS	0.23 Mt/a	-
	Alt. raw material	Mill scale	5.1 kt/a	-
Wu'an	Clinker substitute	BFS	3870 kt/a	-

The second most common symbiont of the considered cement sites is the power & heat sector (Table 3). In this case, fly & bottom ash recycling of coal fired power and CHP plants is the most conventional activity, i.e. 64% of the document exchanges involving the energy sector, as the reuse of one ton of fly ash (as well as BFS/STS) in cement leads to an equivalent reduction of about 770 kg of CO_2 [7]. Furthermore, fly ash adds strength and durability to concrete, as the concrete is more dense and therefore less prone to decline due to contact with sulphur [21]. An indirect combustion by-product, which is also being utilized as secondary raw material on two sites (Aalborg and Wu'an), is FGD gypsum, a by-product of flue gas desulfurization (FGD). The plant in Aalborg also supplies chalk slurry as a desulfurization agent to the partnering power plant. The same plant is also the only cement work that recovers its waste heat for feeding the local district heating (DH) network (335 GWh/a), which is the only documented energy exchange in this study.

Table 3: IS activities involving the power & heat sector

Site	IS activity	Stream	Magnitude	Benefit
Aalborg	Clinker substitute	Fly ash	200 kt/a	-
	Alt. raw material	FGD gypsum	57 kt/a	-
	Waste heat for DH	Excess Heat	335 GWh/a	-
	Desulphurization	Chalk slurry	10 kt/a	-
Dunbar	Clinker substitute	Fly & bottom ash	500 kt/a	
Gladstone	Clinker substitute	Fly ash	40 kt/a	-
Rizhao	Clinker substitute	Fly ash	66 kt/a	-
Taranto	Clinker substitute	Fly ash	38 kt/a	-
Wu'an	Alt. raw material	FGD gypsum	20 kt/a	-
	Clinker substitute	Fly ash	35 kt/a	-
Zaozhuang	Clinker substitute	Fly & bottom ash	-	-

Cement production is an energy intensive process with fuel accounting for about one-third of the costs for producing clinker [23]. The main energy consumer is the cement (rotary) kiln, which generates thermal energy by burning fossil fuel, primarily coal, for the calcination (900°C) and sintering (1450°C) processes. The rotary kiln used in cement manufacturing is able to burn a wide range of materials due to the long residence time at high temperatures, the intrinsic ability for clinker to absorb and lock contaminants into the clinker and the alkalinity of the kiln environment [24]. Therefore, most of the activities with the waste processing sector, i.e. 80 %, circle around the utilization of collected and processed wastes as an alternative cement kiln fuel (Table 4). This enables the participating cement actors to remain economically competitive and, in case of organic wastes

(Aalborg, Kawasaki), to reduce their CO_2 emissions. Apart from valorising its caloric value, waste is also used as a secondary raw material, such as the reuse of WW sludge for limestone substitution in Kawasaki.

Table 4: IS activities involving the waste processing sector

Site	IS activity	Stream	Magnitude	Benefit
Aalborg	Alternative fuel	Dried WW sludge	4000 t/a	-
	Alternative fuel	Industry waste	-	-
Dunbar	Alternative fuel	Recycled liquid fuel (RLF)	22 kt/a	40 kt/a coal saved
Gladstone	Alternative fuel	Solvent based fuels	2500 m^3/a	-
Kawasaki	Alternative fuel	Waste plastics	6.75 kt/a	9.1 kt/a coal saved
	Alternative fuel	Organic waste	14.86 kt/a	-
	Alternative fuel	Soot, other burned residue	0.7 kt/a	-
	Alt. raw material	Construction soil	-	-
	Limestone substitution	WW sludge	20 kt/a	55 kt/a limestone saved
Midlothian	Alternative fuel	Waste plastics	-	-

The main disadvantage of secondary raw material such as BFS (Table 2) and fly ash (Table 3) is the potential reduction in their availability in enough quantities for cement production, with the expected decline in the use of coal in power & heat generation and steel manufacturing (secondary steelmaking). On the other side, the generation of paper sludge, a by-product of pulping, papermaking, and deinking processes, is expected to increase due to higher paper recycling rates (e.g. 300 kg sludge per ton of recycled paper generated [25]). Since paper sludge consists primarily of cellulose fibres and fillers such as calcium carbonate and kaolinite, it can be used to substitute limestone (Aalborg) and clay (Kawasaki). An additional alternative calcium source for clinker production is also white or lime sludge (Guitang, Rizhao), which is usually utilised in the paper mill on-site in the lime oven. Additionally, in Rizhau (Table 5) fly ash from the coal fired boiler of the pulp and paper plant is being send to the neighbouring cement plant.

Table 5: IS activities involving the paper & pulp sector

Site	IS activity	Stream	Magnitude	Benefit
Aalborg	Alt. raw material	Paper sludge	1700 t/a	-
Guitang	Alt. raw material	White sludge	-	-
Kawasaki	Clay substitution	Paper sludge	16.8 kt/a	263 kt/a clay saved
Rizhao	Clinker substitute	Fly ash	66 kt/a	-
	Alt. raw material	White sludge	70 kt/a	-

Due to the nature of the raw materials used and the manufacturing processes involved in the production of minerals (quarrying, crushing, grinding, drying), only material exchanges, in form of alternative raw materials, are present between the mineral and cement sector (Table 6). Although the sectors share some common raw materials, such as limestone, the shared streams originate primarily from the mineral site, as the latter has significantly higher quality and purity requirements as the cement sector. The only symbiotic activity in which the involved cement plant acts as a donor, is the valorisation of LKD from the cement and lime mill in Kwinana for chlorine removal in the adjacent pigment factory.

Table 6: IS activities involving the mineral sector

Site	IS activity	Stream	Magnitude	Benefit
Kwinana	Alt. raw material	Shale	-	-
	Clinker substitute	BFS	-	-
	Chlorine removal	LKD	-	-
Wu'an	Alt. raw material	Limestone and sandstone fines	1200 kt/a	-

As the chemical industry is more diverse than any other process industry, it comes as no surprise that all of the reviewed IS activates revolving around the chemical sector feature a different shared stream (Table 7). Aalborg Portland, for example, buys iron oxide (pyrite ash) from a sulphuric acid manufacturer and reuses bone mean from a biodiesel plant as alternative cement kiln fuel, while the Kwinana cement plant valorises the spend residue cracking unit (RCU) catalysts from the nearby refinery as a an alternate pozzolan (Si, Al). On the other hand, the cement mill in Zaozhuang receives bottom and fly ash from the coal fired boilers of an ammonia plant.

Table 7: IS activities involving the chemical sector

Site	IS activity	Stream	Magnitude	Benefit
Aalborg	Alt. raw material	Iron oxide	45 kt/a	-
	Alternative fuel	Bone meal	-	-
Kwinana	Alt. raw material	Spend RCU catalysts	-	-
Zaozhuang	Clinker substitute	Bottom & Fly Ash	-	-

More particular IS activities (more than 14%) involve actors from a variety of different sectors, e.g. from food and textile to rubber, glass and non-ferrous metal (Figure 1). A very interesting case is the utilization of sand dredged from the Limfjord fjord in Aalborg (Table 8). Recycled sand and glass from a glass factory is also used in the Dunbar cement mill, which at the same time reuses the scrap tires from a tire plant as an alternative cement kiln fuel. In Gladstone the spent cell linings (SCL) from aluminium smelter are valorised both as alternative fuel and raw material in clinker production. Vice-versa the cement works in Kwinana sells its LKD to various companies for soil conditioning. In contrast to the other analysed sites, a sugar refinery is the main facilitator of IS in Guitang. Namely, it sends both filter sludge and fly ash to the neighbouring cement plant.

Table 8: IS activities involving other sectors

Site	IS activity	Stream	Magnitude	Benefit
Aalborg	Alt. raw material	Sand from dredging	80 kt/a	-
Dunbar	Alt. raw material	Recycled glass/sand	-	
	Alt. fuel	Scrap tires	20 kt/a	41 kt/a of coal saved
Gladstone	Alt. fuel & raw material	SCL	12 kt/a	-
Guitang	Alt. raw material	Filter sludge	-	-
	Clinker substitute	Fly ash	-	-
Kwinana	Soil conditioning	LKD	-	-
Zaozhuang	Clinker substitute	Bottom & Fly Ash	-	-

3.2 Future plans

5 out of the 16 analysed cement sites have future plans to extend their current IS activities (Table 9). As with the already successfully implemented symbiotic exchanges, most cement plants aim to introduce new supplementary cementitious materials (Gladstone, Liuzhou) or alternative raw materials (Kwinana, Liuzhou) in order to reduce their production costs. In Kwinana, for instance, there are proposals to reuse the spent graphite electrodes of a steelmaker's electric arc furnace (EAF) as a secondary raw material. On the other hand, two plants, i.e. IJmuiden and Zaozhuang, intend to lower their GHG emissions by using excess steam from the neighbouring industries as an

alternative energy source. Another interesting idea from the IJmuiden site is the proposed sharing of the residing steel mill's wastewater treatment facility with the adjacent cement works. The cement plant in Kwinana is also thinking about lowering its fresh water consumption by using wastewater from the nearby treatment facility as process and/or washing water.

Table 9: Future plans to extend the IS activities of reviewed cement sites

Site	IS activity	Stream	Symbiont
Gladstone	Clinker substitute	BFS	Steel
IJmuiden	Alt. energy source	Excess steam	Steel
	Facility sharing	WW treatment	Steel
Kwinana	Alt. raw material	Spent graphite electrodes	Steel
	Alt. energy source	Excess steam	Non-ferrous metal
	Alt. raw material	FGD gypsum	Non-ferrous metal
	Alt. water source	WW	Waste processing
Liuzhou	Clinker substitute	Fly ash	Power & Heat
Zaozhuang	Alt. raw material	FGD gypsum	Power & Heat

3 Conclusion

In order to preserve its competitiveness and retain the current number of work places in the European cement industry as well as to meet stricter emission standards (e.g. Paris Agreement) the implementation of industrial symbiosis activities is an unavoidable measure. In this paper, a review of successful industrial symbiosis case studies in the cement industry was performed. In total, 16 cement manufactures, from 9 different countries, were analysed.

While IS activities in 9 of the considered sites were induced though government initiatives, like the Chinese Five-year Development Plan, the Japanese Eco-Town program or the South Korean EIP initiative, the rest of the documented symbiotic connections were formed spontaneously by the motivation of cost reduction. The number of IS exchanges per site varies between 10 in and 1 (Table 1), with an average value of 2.8 for sites with government initiated IS and 4.3 for sites with spontaneously formed IS activities. Hence, there is no obvious correlation between the number of exchanges and the IS driving factor.

In 46 out of the 56 documented IS activities across 16 sites, i.e. in more than 82%, solids are being exchanged between the involved actors. They are followed with a wide margin by liquids and chemicals with 12.5% and 3.6%, respectively. On the other hand, the most rarely exchanged stream type is energy, i.e. only one case. The latter seems like an untapped opportunity with regard to the available excess heat (35% of primary energy use [26], 100-450 °C [27]). However, there are two main factors limiting the expansion of waste heat valorisation. First, since cement manufacturing is an energy intensive process, most waste heat is utilized internally on site, e.g. combustion air preheating, drying, etc. This is also the most cost effective and energy efficient way, since heat and pressure losses limit the proximity and temperature level of potential heat sinks (e.g. maximal distance between a heat source and district heating network about 30 km). One approach to overcome this barrier is to use excess heat to produce electricity, which can not only be transferred over significantly longer distances with minor losses but can also be converted to an arbitrary form of energy at the receiver site. This can be achieved with the application of the organic Rankine cycle (ORC) and the Kalina cycle, which are Rankine based cycles, for converting heat to electricity.

The above-mentioned limitations of energy streams partly explain the widespread exchange of solid streams, since apart from their abundancy (e.g. slag generation approximately 10–15% of crude steel output) they can also be easily transported outside the site of origin or the corresponding industrial park borders due to their easily manageable (stable) characteristics, and lower hazard and risk potential, especially compared to other stream types. The most commonly shared streams include fly ash from coal fired boilers and furnaces, and BFS/STS from the steelmaking industry (11 documented cases each). As both of these by-products can be used to substitute cement clinker, their use cannot only reduce the cost for raw material but, more importantly, significantly decrease the energy consumption and consequently the GHG emissions of a cement plant, i.e. the clinker calcination process represents about 90% of total energy use during cement manufacturing. On the other side, the potential disadvantage of BFS and fly ash is the probable reduction in their availability in sufficient quantities for cement production, with the expected decline in the use of coal in energy generation and steel manufacturing (EAF route). Therefore, paper sludge represents an attractive alternative, as its generation is expected to increase due to higher paper recycling rates.

Another major opportunity to lower the production costs of cement is the use of alternative cement kiln fuels, especially those of biogenic origin, such as WW sludge, that also enable a reduction of GHG emissions. A different approach to lower CO_2 emissions, is to apply carbon capture and storage (CCS) technologies as for example calcium looping [28], which can be used to capture the CO_2 released during the calcination process. The captured CO_2 could then be stored and sold to industries that directly utilize CO_2, e.g. as carbonating agent, preservative, packaging gas etc.

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