LIFE-CYCLE IMPACTS AND COSTS OF MANGANESE LOSSES AND RECOVERY DURING FERROMANGANESE PRODUCTION

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ABSTRACT

Manganese mines and ferromanganese producers are facing increased pressure from rising operating costs, reducing margins, and increasingly stringent environmental regulations. As price takers, manganese producers must look internally for operational and productivity improvements in order to enhance margins and maintain competitiveness.

Although multiple tools are available for identifying operational improvements, most are focused on one process stage, department or discipline. Life Cycle Assessment (LCA) is a tool that provides a broader perspective to create bridges across multiple departments, allowing senior managers to visualize the full supply chain prior to making decisions. Conventionally LCA is used for environmental analysis, modelling and reporting. Hatch has successfully adopted LCA methodologies to simultaneously use the results to identify viable productivity improvement, energy optimization and emissions reduction opportunities through the combined experience of its in-house operations, energy, and sustainability experts.

Hatch and the International Manganese Institute recently completed the first globally representative LCA of manganese alloy production, involving primary site data from 17 manganese mines and smelters. The LCA provides industry-sourced process and environmental data for representing all the inputs required for the production of a unit of silicomanganese, ferromanganese and refined ferromanganese. The LCA helps evaluate the environmental performance of the industry as well as provides useful information to benchmark processes and generate cost and environmental performance improvement opportunities.

This paper applies the results of the manganese LCA to measure the costs and impacts of manganese losses occurring along the ferromanganese supply chain. The analysis assesses the cumulative supply chain cost, environmental and throughput benefits associated with projects to enhance manganese recovery at each process stage. The paper concludes that manganese recovery downstream has a compounded benefit on upstream processes and operating costs. By employing enhanced manganese recovery systems and management procedures, manganese producers can reduce energy, costs and GHG emissions.

1. INTRODUCTION

Life Cycle Assessment (LCA) is one of the leading tools used to evaluate the environmental performance of supply chains and product systems. LCA provides an aggregated assessment of a wide range of potential environmental impacts of a supply chain based on mass-energy balance models which extend beyond traditional site boundaries to include associated upstream and downstream processes such as power generation, coal mining and hazardous waste management. As a tool standardized by the International Organization for Standardization (ISO 14040:2006; 14044:2006) [1, 2] and the precursor to greenhouse gas (GHG) reporting protocols, LCA is broadly accepted and applied within several industry sectors including metals and mining.

Hatch and the International Manganese Institute (IMnI) recently completed the first LCA of global manganese alloy production. The study, spanning 17 manganese mine and smelter facilities, provided the industry and its stakeholders with a standard measure of average industry environmental performance for release of GHGs, particulate matter (PM), NO_X and SO_X, as well as water and energy consumption, and waste generation [3]. By novel approaches to the LCA modelling process, the study also utilized the mass-energy model underlying the LCA method to use the LCA as a benchmarking tool within the industry to evaluate and help identify process efficiency, throughput and emissions optimization opportunities. By linking processes across the entire manganese supply chain, the LCA can be a powerful tool to examine throughput, energy and emissions flows across an entire supply chain or process route, and provides useful information about the inter-relationship between unit processes.

This paper illustrates the potential benefit of applying LCA as a process optimization tool for the manganese industry. In the paper, LCA is applied to evaluate the benefits of enhanced manganese recovery along the ferromanganese supply chain aiming at providing contextual information regarding investments. The approach can be similarly adopted to apply LCA data to silicomanganese and refined ferromanganese alloys however have not been included in this paper in the interests of brevity.

2. METHODOLOGY

2.1 LCA Methods

LCA uses a mass-energy balance model to provide a series of metrics measuring the environmental emissions, energy and resource consumption of a product or process chain. LCAs are conducted using a standardized methodology defined by ISO 14040 and ISO 14044 standards consisting of the following four phases:

- Goal and Scope Definition – which clearly defines the objectives and intended audience of the study, with consistent system boundaries, product systems and environmental impact categories and metrics;
- Life Cycle Inventory (LCI) – which involves the establishment of mass-energy based models consisting of unit processes linked by flows of energy, consumables, emissions and other flows to represent the entire product system;
- Life Cycle Impact Assessment (LCIA) – which uses established weightings to relate emission flows such as carbon dioxide and methane emissions to potential environmental impacts such as global warming potential; and
- Interpretation – an iterative phase to validate, evaluate and qualify the inputs and results of the study.

Traditional LCAs typically aim at providing data for external industry stakeholders, including consumers, regulators, and the general public, as well as to optimize the environmental impacts of the supply chain itself. In the manganese LCA, novel approaches to modeling and data management focused on using the LCA to provide benchmark data to allow individual producers an ability to evaluate specific processes against industry averages. The empirical benchmark data compliments detailed theoretical evaluation and numerical simulation by targeting specific areas for management and technological improvement, including cost and process optimization in addition to environmental benefit.

2.2 Modelling Manganese Recovery and Losses

Metal losses have an important impact on the ferromanganese supply chain, requiring additional manganese-bearing material from upstream processes to replace losses occurring at any given stage of production. Any additional manganese required to account for losses must be carried through the supply chain, incurring additional conversion costs and increasing total emissions generated for each tonne of ferromanganese produced.

The impacts associated with manganese losses are evaluated at each stage of production by calculating the cumulative impact on supply chain costs, consumables and emissions. In each case, the costs of manganese losses are captured by considering the impacts associated with a 1% increase in the recovery rate of each stage of production. A 1% increase in recovery rate at a stage, *i*, reduces the costs, consumables and throughput of each previous stage of production by a factor, X_i, at each previous stage of production, relative to a unit of ferromanganese production:

$$X_i = \frac{1}{1+1\%\frac{}{R_i}} \qquad (1)$$

Where R_i is the average recovery rate of stage *i*.

Costs have been considered for energy inputs consumed due to the manganese loss effect based on typical industry prices listed in Table 5 below.

Table 5: Indicative input costs used in conversion cost evaluation.

Material/Energy	Cost (USD)
Manganese Ore	\$140/t
Manganese Sinter	\$224/t
Ferromanganese Alloy	\$872
Electricity	\$70/MWh
Diesel	\$1.05/L
Coal	\$65/t
Coke	\$250/t

Manganese recovery rate and losses are considered relative to typical global industry averages as determined by the LCA study for the ferromanganese supply chain. The cumulative benefits of manganese recovery at a given process stage is the sum of the benefits achieved at and upstream of the process stage as determined by Equation 1.

3. OVERVIEW OF MANGANESE LIFE-CYCLE

The manganese LCA covered all primary processes from extraction of ore up to and including manganese alloy production, as well as secondary processes not directly managed by manganese producers, including coal mining, coke production, electricity production and transportation. Figure 13 illustrates the system boundaries considered by the LCA and in the evaluation of manganese losses and recovery.

For the purposes of this analysis, the LCA supply chain has been grouped into the following categories:

- Mineral extraction and hauling;
- Ore processing, beneficiation and delivery;
- Sinter production and delivery;
- Ferromanganese smelting (furnace production); and
- Metal casting, crushing and screening, materials handling and other auxiliary smelter activities.

17 facilities included in the global manganese LCA comprised both surface and underground mines. Surface mines are characterized by high diesel consumption and generation of overburden and waste rock relative to run-of-mine (ROM) ore produced. Underground mines tend to have higher electricity consumption while generating less waste materials during extraction. Ore processing and beneficiation activities included in the study comprised crushing, screening, dense media separation, tailings management and on-site diesel generating stations. Upstream processes considered for manganese mining consist of diesel refining and transportation, grid power generation, tyre manufacturing and other related processes.

Sinter formed a portion of the manganese-bearing charge to ferromanganese furnaces. Sinter production considers the ore and carbon charge, ignition source, and emissions generated by the process. The fuel and emissions associated with ore and sinter transportation between mine and smelter sites are distributed proportionally (by mass) to ore and sinter processing.

Ore and sinter form the majority of manganese-bearing materials charged to ferromanganese furnaces, in addition to small amounts of internally recovered manganese materials. In addition to the consumables and emissions generated at the furnace, the study also considers the associated upstream processes including the extraction, generation and transportation of fluxes, reductants, and grid power delivered to the furnace. In some cases ferromanganese slag generated at the furnace is recovered in siliconmanganese production, which has not been explicitly considered in the present examination.

Other than the furnace operation, activities at the smelter include processing of feed materials and furnace outputs, including slag processing and metal recovery, and metal casting, crushing and screening to final product size.

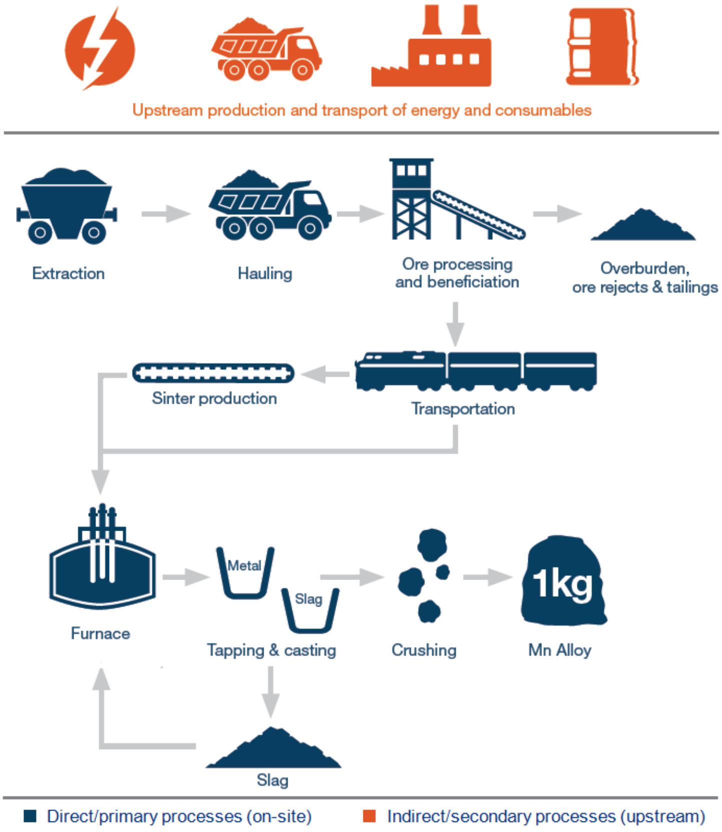

Figure 13: Schematic representation of the system boundaries considered for ferromanganese alloy production.

4. AVERAGE MANGANESE LOSSES

Manganese losses occur at each stage of the ferromanganese supply chain through different waste and by-product flows. At ore processing and beneficiation, manganese is lost to waste ore and tailings as an expense associated with sizing the ore and raising the manganese content of the saleable product. Losses during sinter production can occur through particulate matter generation and in fines losses. During smelting, manganese losses flow primarily to slag, and to a lesser extent to stack emissions, baghouse dusts and sludge. Internal recycle loops, including slag metal recovery and recycling of baghouse dusts and sludges reduce losses and have been netted out from the smelter balance in this analysis. Losses during casting, crushing and screening include un-recovered metal from the runners, cast beds, and crushing and screening area. Metal losses at crushing and screening are the largest for mechanical processed metal, as opposed to manual processing, which generates very little losses.

Manganese losses at each stage of production are shown in

Table **6** for industry average ferromanganese production. Most losses occur during ore processing and ferromanganese smelting. The lowest recovery rate (relative to manganese input) occurs during smelting. While the recovery rate at casting crushing and screening is highest, losses at this stage have the largest cumulative impact on the entire supply chain, requiring increased production at all successive upstream processes. Across the entire supply chain, up to a third of manganese contained in the extracted-run-of-mine ore is lost in the production of ferromanganese alloy.

The losses incurred at each stage of production can put in the context of the net value added by the process stage. Figure 14 presents cumulative manganese losses at each stage of ferromanganese production. Here the largest manganese losses are incurred in conjunction with the largest removal of non-manganese bearing materials. With this perspective, some manganese losses may be considered more acceptable than others. However, for the present analysis, the value placed on manganese losses at each stage is based solely on the additional energy, consumables and throughput required at each upstream process stage to offset marginal losses occurring at various points along the ferromanganese supply chain.

Table 6: Industry average manganese losses and recovery rate per process stage.

Process Stage	Recovery Rate (% of Mn-Input)	Manganese Losses (kg/t-alloy)
Ore Processing & Beneficiation	87.5%	140
Sinter Production	87.5%	40
Smelting	84.0%	150
Casting, Crushing & Screening	97.5%	20
Total Supply Chain	68.8%	350

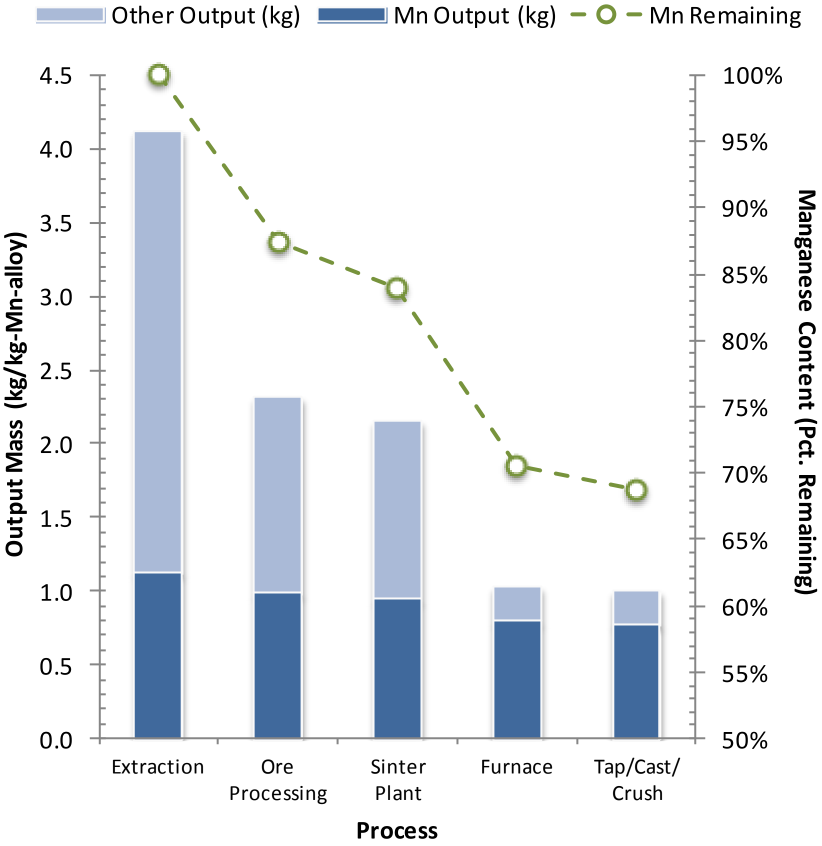

Figure 14: Manganese throughput and losses by supply chain stage for industry average ferromanganese production.

5. ENERGY CARRIERS AND GREENHOUSE GAS EMISSIONS

Each stage in the supply chain involves additive costs and environmental impacts associated in additive processing and consumption of consumables. Table 7 lists a breakdown of total energy consumption (Primary Energy Demand), GHG emissions (Global Warming Potential) and key energy and reductant consumables at each stage of industry average ferromanganese production. The figures below implicitly include the impacts of manganese lost at each successive process stage, which acts to increase the total energy and environmental impacts of the supply chain. Similarly, reducing manganese losses acts to streamline the throughput of manganese through the supply chain thereby reducing the amount of manganese, material, and energy required at each processing stage.

Table 7: Industry average energy consumption and greenhouse gas emissions by supply chain stage per tonne of ferromanganese production.

Process Stage	Primary Energy Demand (GJ)	Global Warming Potential (tCO2e)	Grid Power (kWh)	Diesel (kg)	Coal (kg)	Coke (kg)	Explosives (kg)
Extraction	0.6	0.08		13.9			3.2
Ore Processing & Beneficiation	0.9	0.10	37	19.0			
Sinter Production	3.0	0.30	32	7.3	35	49	
Smelting	26.0	4.27	2811		149	372	
Casting, Crushing & Screening	1.4	0.31	268	3.5			
Total Supply Chain	**31.9**	**5.06**	**3148**	**43.6**	**184**	**421**	**3.2**

6. BENEFITS OF MANGANESE RECOVERY

Manganese recovery achieves a cumulative benefit at each upstream process along the supply chain by avoiding consumables, emissions and increased costs incurred in processing additional manganese to maintain current levels of production. To evaluate the benefits of manganese recovery, the cumulative life-cycle effects were compared with scenarios where the manganese recovery rate was increased by 1% at a given process stage along the ferromanganese supply chain. Figure 15 below shows the effect of a 1% increase in the recovery rate at casting, crushing and screening (i.e. a 97.5% to 98.5% recovery increase). While the 1% boost in recovery rate (equivalent to 8 kg/t-alloy produced) reduces energy consumption by 14 MJ/t at casting, crushing, and screening, the total life-cycle savings amount to over 324 MJ/t-alloy when factoring in the upstream supply chain effect.

The cumulative life-cycle effect magnifies the benefit of proportionally modest increases in recovery, especially for processes occurring downstream on the supply chain. Table 8 shows the cumulative life-cycle benefit of manganese recovery at various stages of production on GHG emissions and energy consumables. Table 9 translates this benefit to a total life-cycle cost reduction based on indicative pricing of key consumables. Increasing the recovery rate of downstream processes has a larger cumulative benefit to the manganese supply chain, by reducing the manganese throughput requirements of upstream processes. The largest savings can be achieved by improving the recovery rate of manganese at the furnace and during metal casting, crushing and screening. A 1% recovery rate boost at the furnace and at casting, crushing and screening corresponds to 9 kg/t and 8 kg/t increases in manganese recovery, respectively, leading to a cost reduction of $4.37 and $4.01 per tonne of saleable ferromanganese alloy.

Figure 16 compares the potential cost reductions achieved for each 1% increase in manganese recovery occurring at various stages of ferromanganese production relative to a range of profit margins indicative of the ferromanganese industry. As profit margins tighten over time, the relative importance of identifying and implementing manganese recovery opportunities increases. While the energy cost reductions are achieved throughout the supply chain, the cost savings should be transferred through reduced ore and sinter prices to be realized at the process achieving the reductions. Alternatively, the increased recovery is realized instead by increased production without increase in production costs.

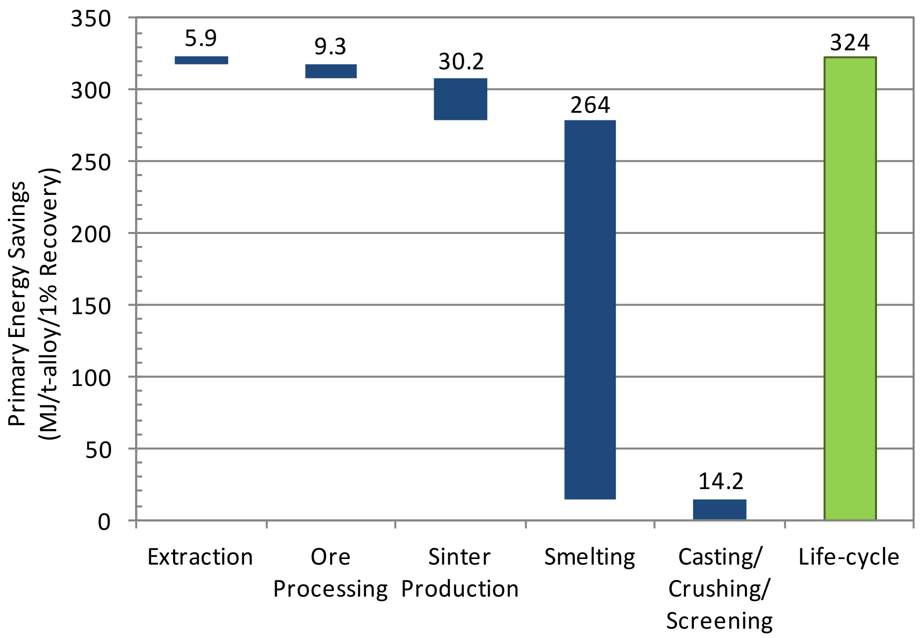

Figure 15: Primary energy reductions at upstream process stages as a result of a plus 1% increase in manganese recovery rate at casting, crushing and screening.

Table 8: Cumulative life-cycle benefits of a plus 1% increase in manganese recovery rate at various points along the ferromanganese production chain relative to industry average production.*

Process Stage of Enhanced Recovery	**Manganese Recovered (kg)**	**Primary Energy Demand**	**Global Warming Potential**	**Grid Power**	**Diesel**	**Coal**	**Coke**	**Explosives**
Ore Processing & Beneficiation	12.7 kg	0.05%	0.04%	0.01%	0.85%	N/A	N/A	1.13%
Sinter Production	4.1 kg	0.12%	0.08%	0.02%	0.47%	0.21%	0.13%	0.37%
Smelting	13.2 kg	1.12%	1.10%	1.08%	1.08%	1.18%	1.18%	1.18%
Casting, Crushing & Screening	11.4 kg	1.02%	1.02%	1.02%	1.02%	1.02%	1.02%	1.02%

* Percent reduction in consumables and emissions per 1% increase in manganese recovery rate relative to industry average production.

Table 9: Cumulative life-cycle energy cost savings of a plus 1% increase in manganese recovery rate at various points along the ferromanganese production chain relative to industry average production.*

Process Stage of Enhanced Recovery	**Life-Cycle Energy Savings (USD/t-alloy/1% Recovery)**
Ore Processing & Beneficiation	$0.52
Sinter Production	$0.46
Smelting	$4.37
Casting, Crushing & Screening	$4.01

* Percent reduction in energy costs per 1% increase in recovery rate relative to industry average production.

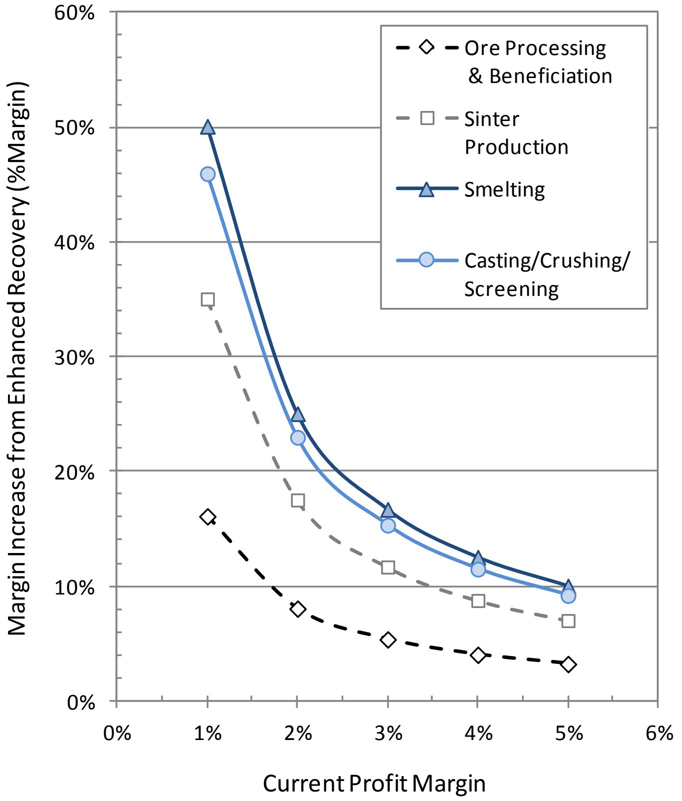

Figure 16: Indicative profit margin increase for a plus 1% enhanced recovery rate occurring at various points along the ferromanganese supply chain. Enhanced recovery occurring during mining and sinter production (dashed lines) are relative to ore and sinter prices, respectively.

7. CONCLUSIONS

LCA provides empirical process data which can help to benchmark processes against industry averages, and determine the links between processes across an entire supply chain. In the current analysis, LCA data representing 17 manganese mines and smelters were used to compare the potential life-cycle benefits of improving manganese recovery at various points along the ferromanganese supply chain. The analysis found that recovery at downstream processes has the largest benefit, by leading to cumulative upstream benefits relative to each unit of ferromanganese produced. While the study applied industry averaged data and approximate costs, analysis of an individual producer may identify new results and correlations for individual value chains. Enhanced manganese recovery can have an appreciable benefit on profit margins for both mines and smelters, especially for sites operating on narrow profit margins. This analysis approach provides a quantitative estimate of the potential operating cost savings from enhanced manganese recovery and may warrant further investigation into the costs of management and technological solutions to improving manganese recovery across the ferromanganese supply chain. By using LCA data, operators can have a more holistic view of where losses occur, value is generated and improvement opportunities reside within the manganese supply chain. Thus the LCA can be used as an important tool for guiding investment decisions across a value chain when capital and margins are scarce.

8. REFERENCES

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