Supplementary material:

Closing the loop: Quality and quantity of scrap in future European steel production.

Quantifying the scrap quality in the circular future of Europe, from an industrial ecology perspective

Master Industrial ecology thesis research project

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Index:

The existing model, code and data, are available via the university repository.

A. Steel scrap production flow chart

Process diagram of steel production for typical EAF and BF-BOF routes with steel scrap input.

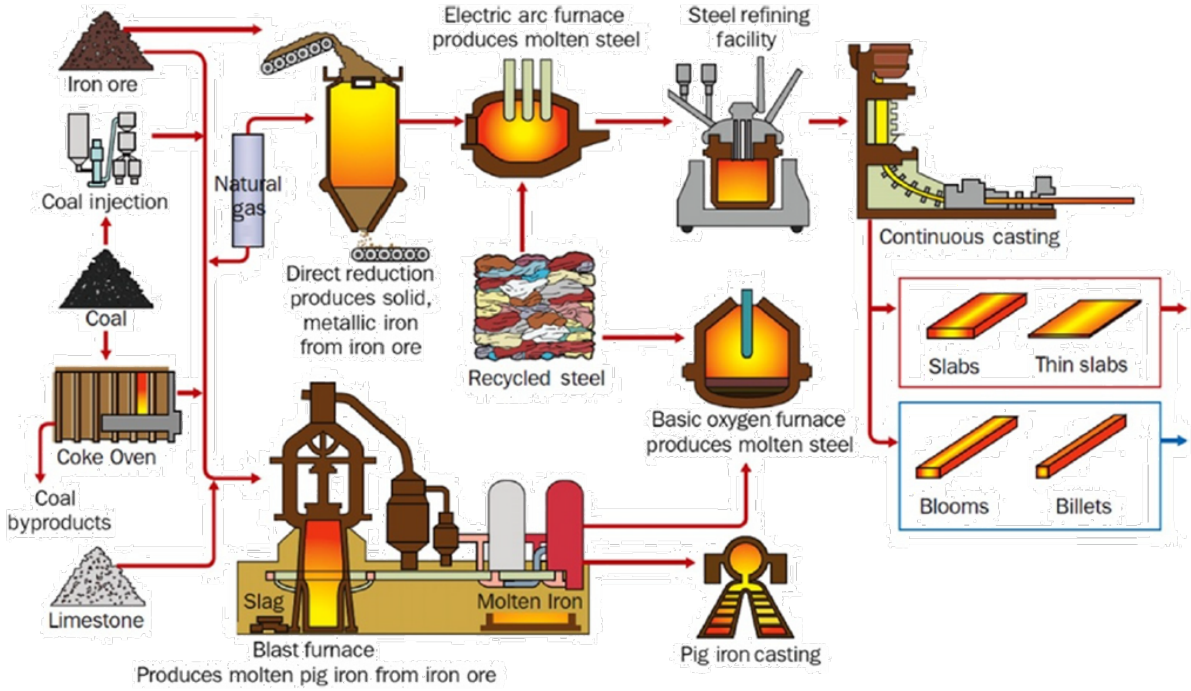


Figure 1: AISTECH conference

B. Tramp elements table

Scrap element information on origin, removal, effects. (Based on Raabe et. al. 2024 and Tata steel experts)

Table B : Tramp elements origin removal and effect on steel quality

Contamination in scrap (Raabe et. al. 2024)

Name	**Origin**		**Removal**	**Effects on steel quality**	**Notes**
	Scrap	**Specific alloys type**			
Copper (Cu)	brass, bronze, coatings, plating, cables , engine parts, electrical gadgets, vehicle scrap, electral and electronic waste	soft magnetic steel weathering steel	improved sorting Vaccuum treatment (to long) Vaccuum remelting (not economic feasible) Theoretical removal Hcontaining plasma treatment, sulfide chloride commercial scale	cracking (hot shortness), scaling behaviour, rolling	Source growing from car schredder. Improving sorting challanging due to high disperion an d solid state intergration. Change in solidification and hot rolling and can mitigate hot shortness. ,Risk of losing valuable metals .
Tin (Sn)	Tin plated packaging material, bronze, tin coating of steels	Formable steel	Electrolytic removal of Sn coating, Removed plasma EAF into dust	Surface cracking (hot rolling	
Chromium (Cr)	Stainless, heat -resitent steel, bearing steels coatings		About half is removed in oxidation	Harder, corosion resistent, detrimental notch impact energy and weldability	85% of world mined chromium is used for stainless, Risk of losing valuable metals .
Nickel (Ni)	Austenitic and duplex stainless steel		Improved sorting , not in liquid steels (noble)	strengthing, brittle fracture	60% of world mined nickel is used in stainless, counteract hot shortness of Cu, Risk of losing valuable metals .

Molybdenum (Mo)	Case-hardened steels , stainless steels		Improved sorting, Not removed from melt and not evaporate.	increase Strength, hardnes, corrosion resitance, impacts welding process	Only dilution ,Risk of losing valuable metals .
Arsenic (As)	Bearings,	Copper alloys		Surface cracking (hot rolling	
Antimony (Sb)	Brasses, Lead-alloys	Corosion resistent		Surface cracking (hot rolling	
Zinc (Zn)	Galvanization (2,8wt% automotive/construction), brass		air and chlorine mixtures	lower Weldability, Toughness, surface quality but improve formability and ductility	Difficulties in production, Environmental problems
Lead (Pb)	Ore, battery components, machining steels,		Vacuum treatment	Improve machining capabilities	Can be removed in slag/vapor or oxide.
Manganese (Mn)	MMnSs steels (manganese steels, 3-12wt%), car scrap, energy absorption bumper		Sulfur and oxygen turn into slag from liquid	Hardening, strength , thermal expansion , decreases thermal and electral conductivity	
Titanium (Ti), Vanadium (V) , Niobium (Nb)	Speciality steels like Tool steels, High performance steels (sheet)	Microalloyed steels	Improved sorting, Not removed from melt and not evaporate.	Multiple microalloying characteristics/goals like strength, hardening	Risk of losing valuable metals .
Silicon	Spring steels		Removed due oxidation, evaporation	Elasticity limits, scale & acid, corossion resitant,	
Aluminium (Al)	Welded components and coatings		Removed due oxidation, evaporation, vacuum degassing	Corossion	

Others	Bromine Br: Cu/Ni_Be alloys for springs, Sulfur from scrap, Phospohous P from iron ore, Lithium (Li) from battery systems

C. The overview of intermediates and the quality in the different sectors

Steel qualities specification for intermediates in the sectors. Adapted from Dworak et al., (2022).

Table E1 Steel qualities (with respect to the tolerance level of the tramp elements Cr, Ni, Cu, Sn and Mo) for each intermediate to end-use sector

		Buildings	Infra-structure	Cars	Trucks	Other Transport	Mechanical Engineering	Electrical Engineering	Other Metal Goods	Domestic appliances	Packaging
9	Electrical Strip							Q1			
10	Tin plated										Q1
11	Plate	Q3	Q3	Q2	Q2	Q2	Q2	Q2	Q2		
12	Cold Rolled Coil galvanized	Q1	Q1	Q1	Q1	Q1	Q1	Q1	Q1	Q1	
13	Cold Rolled Coil coated	Q1	Q1	Q1	Q1	Q1	Q1	Q1	Q1	Q1	
14	Cold Rolled Coil	Q1	Q1	Q1	Q1	Q1	Q1	Q1	Q1	Q1	
15	Hot Rolled galvanized	Q2	Q2								
16	Hot Rolled Narrow Strip	Q2	Q2	Q1	Q1	Q1	Q1	Q1	Q1		
17	Hot Rolled Coil	Q2	Q2	Q1	Q1	Q1	Q1	Q1	Q1		
18	Welded Tube	Q2	Q2		Q2	Q2	Q2	Q2	Q2		
19	Seamless Tube	Q2	Q2	Q2	Q2	Q2	Q2	Q2			
20	Wire Rod	Q3	Q3	Q2	Q2	Q2	Q2	Q2	Q2		
21	Reinforcing Bar	Q4	Q4								
22	Hot Rolled Bar	Q4	Q4	Q3	Q3	Q3	Q3	Q3	Q3		
23	Heavy Section	Q4	Q4								
24	Light Section	Q4	Q4								
25	Rail Section		Q4				Q3				

Steel qualities: **Q1**: < 0.18% for sum of Cu, Cr, Ni, Sn & Mo; **Q2**: 0.18% - 0.25%; **Q3**: 0.25 – 0.35%; **Q4**: > 0.35%

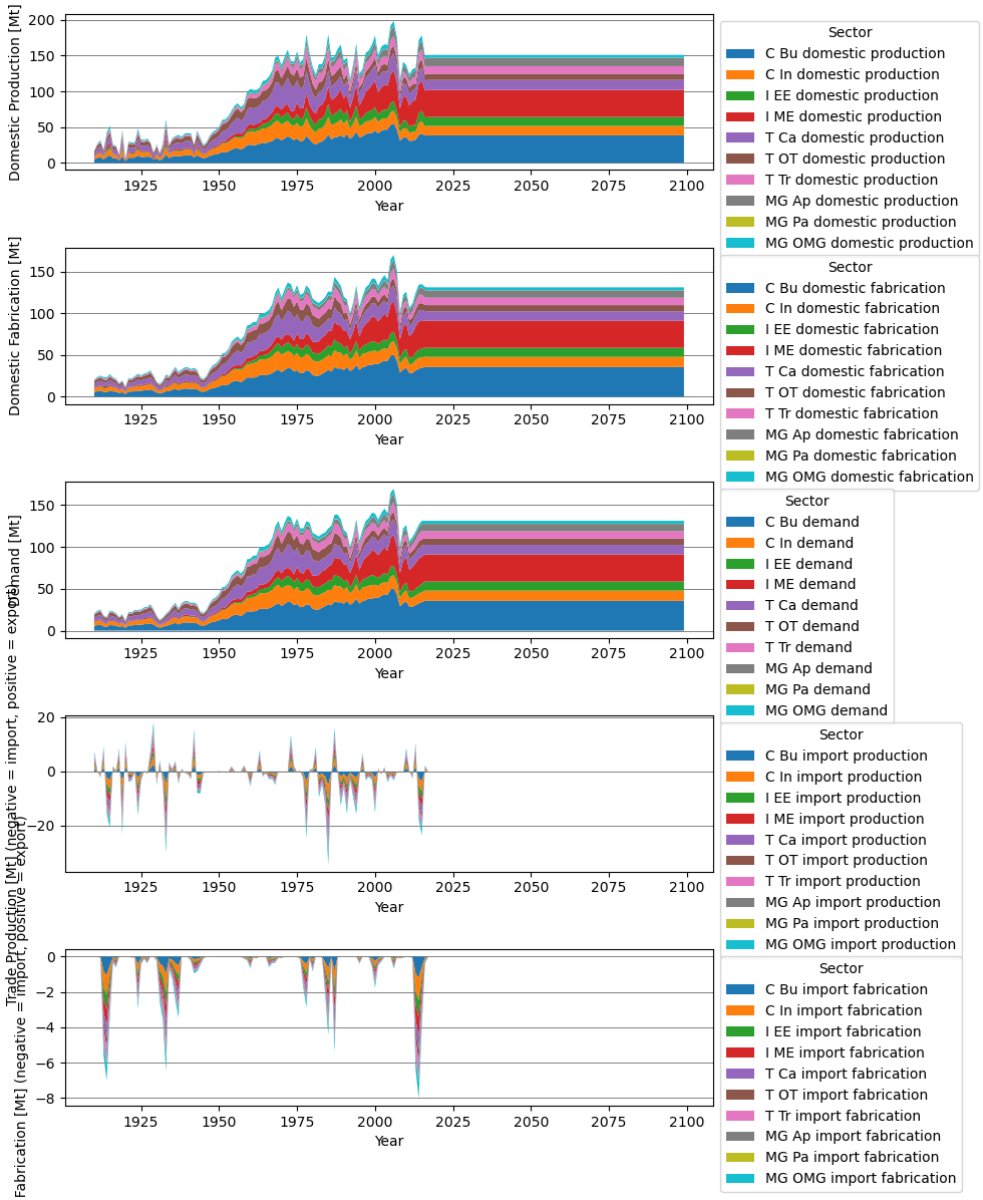
D. Lifetime of products

Table 2: Data on average lifetime EOL export rate and recovery rate per sector.

End use sector	*Average lifetime*	*End of live export rate*	*Recovery rate*	
			<2010	>2050
Construction Building	65	-	82%	87%
Construction Infrastructure	65	-	82%	87%
Transport Car	17	30%	82%	98%
Transport Trucks	17	70%	82%	98%
Transport other	55	-	82%	87%
Industy Mechanical Engineering	17,5	-	87%	91%
Industry Electrical Engineering	15	-	87%	91%
Metal goods Other	14	-	58%	71%
Metal goods Applicanes	14	-	58%	71%
Metal goods packaging	1	-	58%	71%

E. Figure of import export scrap and fabrication and production

S1



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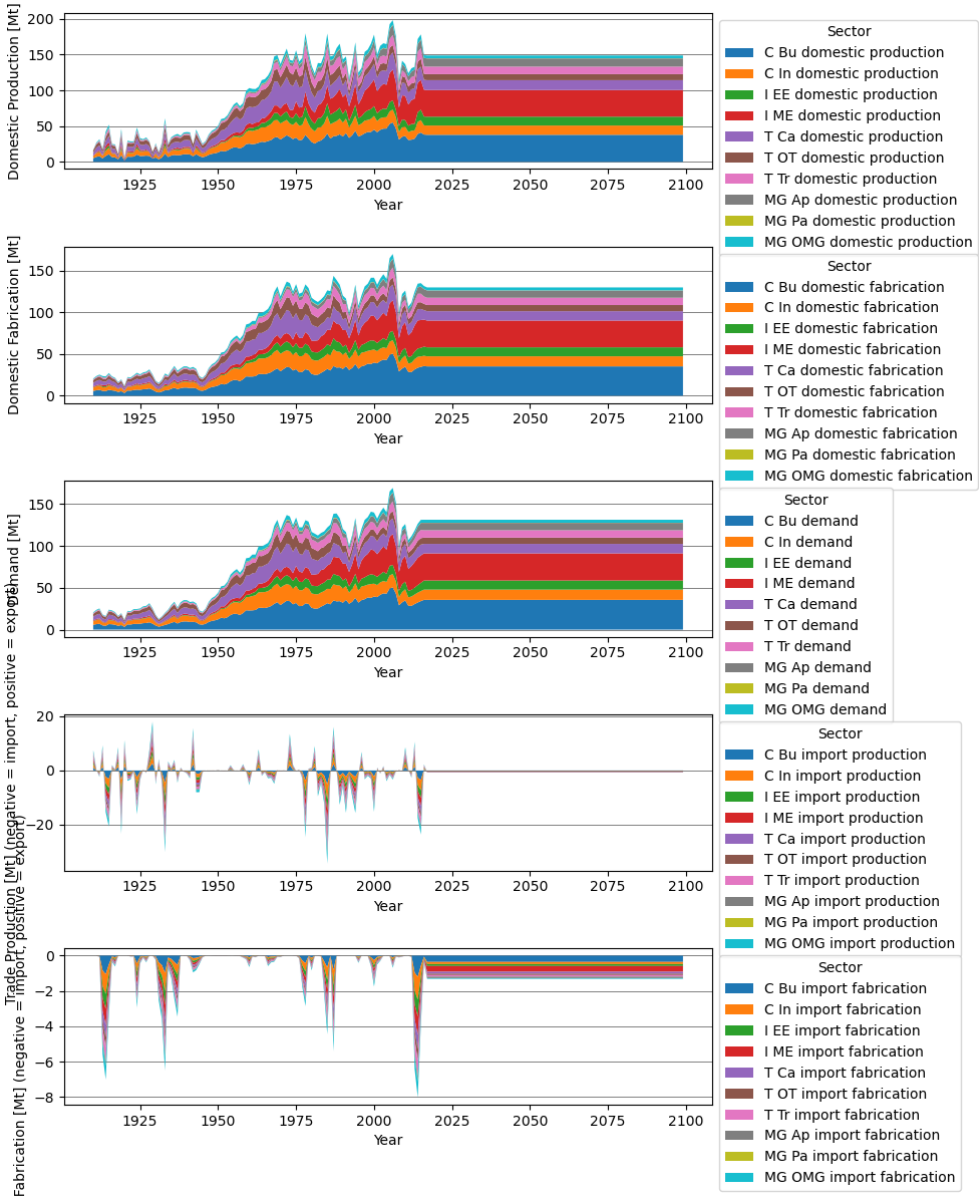
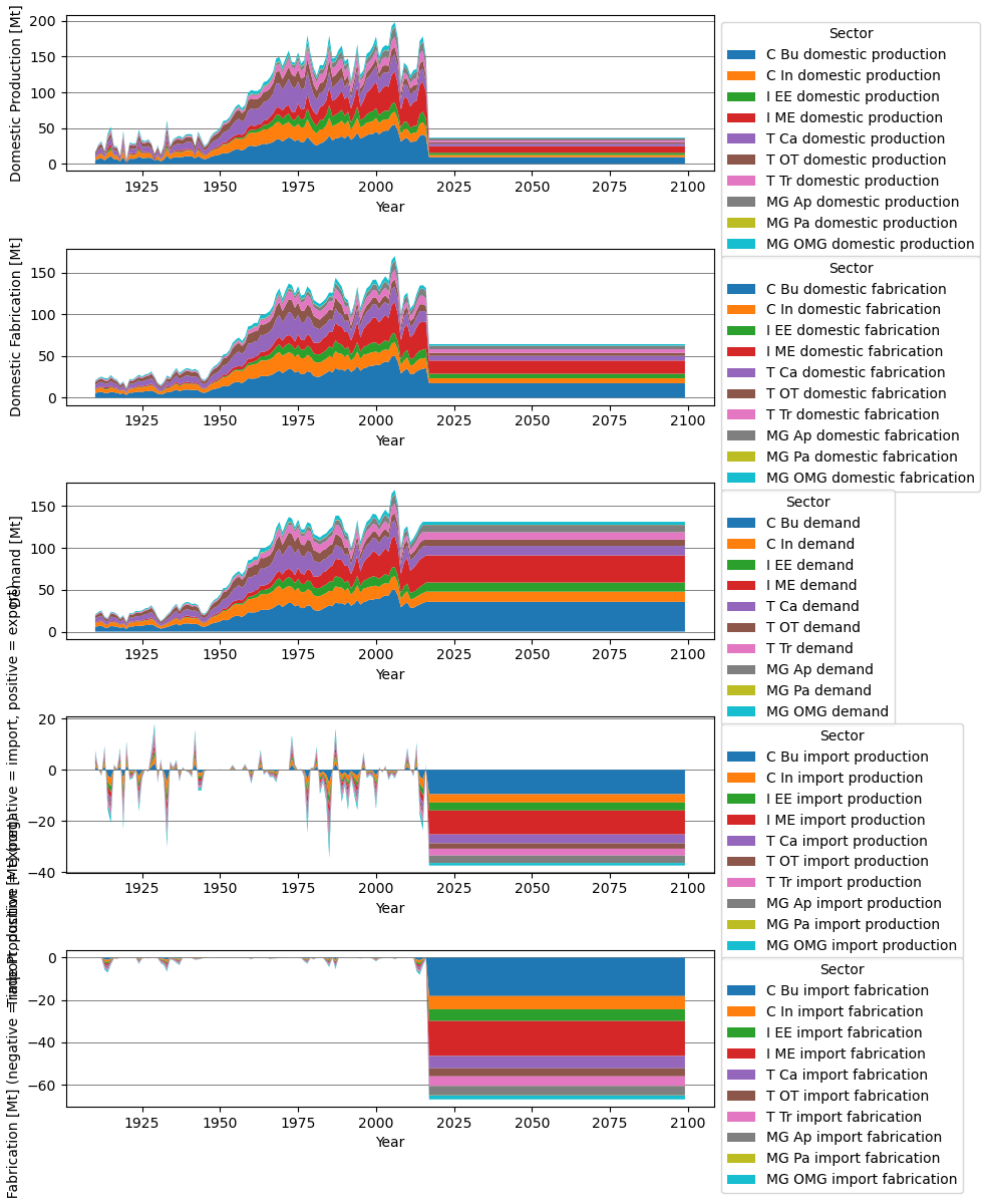

Domestic Production [Mt]
Year
Sector
C Bu domestic production
C In domestic production
I EE domestic production
I ME domestic production
T Ca domestic production
T OT domestic production
T Tr domestic production
MG Ap domestic production
MG Pa domestic production
MG OMG domestic production
Domestic Fabrication [Mt]
Year
Sector
C Bu domestic fabrication
C In domestic fabrication
I EE domestic fabrication
I ME domestic fabrication
T Ca domestic fabrication
T OT domestic fabrication
T Tr domestic fabrication
MG Ap domestic fabrication
MG Pa domestic fabrication
MG OMG domestic fabrication
Demand [Mt]
Year
Sector
C Bu demand
C In demand
I EE demand
I ME demand
T Ca demand
T OT demand
T Tr demand
MG Ap demand
MG Pa demand
MG OMG demand
Trade Production [Mt] (negative = import, positive = export)
Year
Sector
C Bu import production
C In import production
I EE import production
I ME import production
T Ca import production
T OT import production
T Tr import production
MG Ap import production
MG Pa import production
MG OMG import production
Fabrication [Mt] (negative = import, positive = export)
Year
Sector
C Bu import fabrication
C In import fabrication
I EE import fabrication
I ME import fabrication
T Ca import fabrication
T OT import fabrication
T Tr import fabrication
MG Ap import fabrication
MG Pa import fabrication
MG OMG import fabrication

S3


Domestic Production [Mt]
Year
Sector
C Bu domestic production
C In domestic production
I EE domestic production
I ME domestic production
T Ca domestic production
T OT domestic production
T Tr domestic production
MG Ap domestic production
MG Pa domestic production
MG OMG domestic production
Domestic Fabrication [Mt]
Year
Sector
C Bu domestic fabrication
C In domestic fabrication
I EE domestic fabrication
I ME domestic fabrication
T Ca domestic fabrication
T OT domestic fabrication
T Tr domestic fabrication
MG Ap domestic fabrication
MG Pa domestic fabrication
MG OMG domestic fabrication
Year
Sector
C Bu demand
C In demand
I EE demand
I ME demand
T Ca demand
T OT demand
T Tr demand
MG Ap demand
MG Pa demand
MG OMG demand
Year
Sector
C Bu import production
C In import production
I EE import production
I ME import production
T Ca import production
T OT import production
T Tr import production
MG Ap import production
MG Pa import production
MG OMG import production
Year
Sector
C Bu import fabrication
C In import fabrication
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T Ca import fabrication
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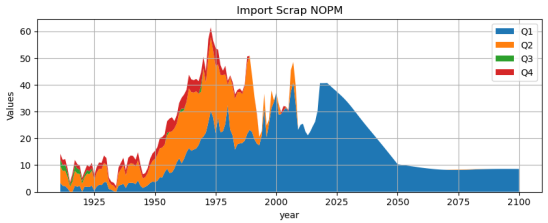
MG Ap import fabrication
MG Pa import fabrication
MG OMG import fabrication

S3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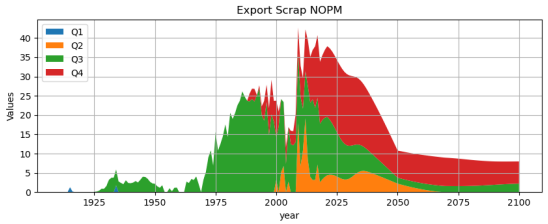
Q1
Q2
Q3
Q4
Values
year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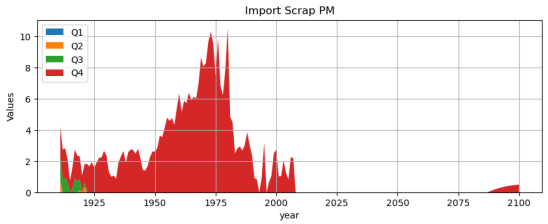
Q1
Q2
Q3
Q4
Values
year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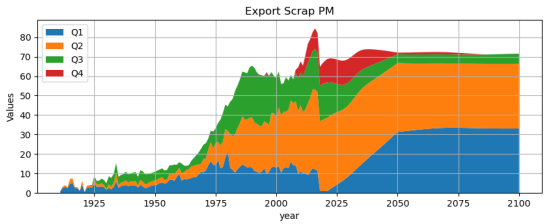
Q1
Q2
Q3
Q4
Values
year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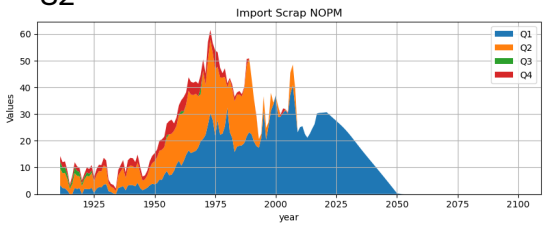
Q2
Q3
Q4
Values
year

S2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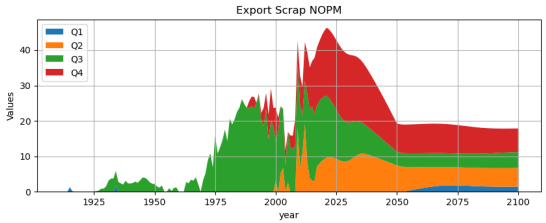
Q1
Q2
Q3
Q4
Values
year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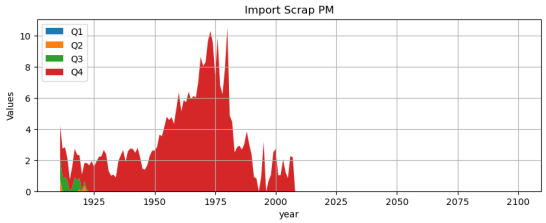
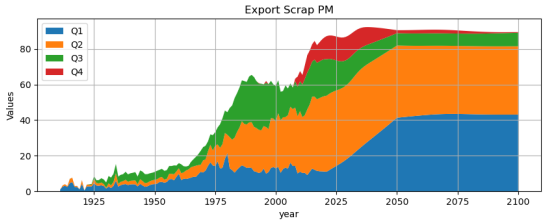
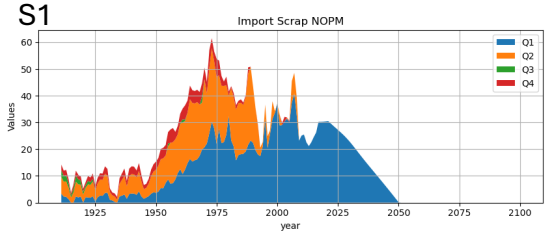
Q2
Q3
Q4
Values
year


Import Scrap PM
Q1
Q2
Q3
Q4
Values
year


Export Scrap PM
Q1
Q2
Q3
Q4
Values
year

S1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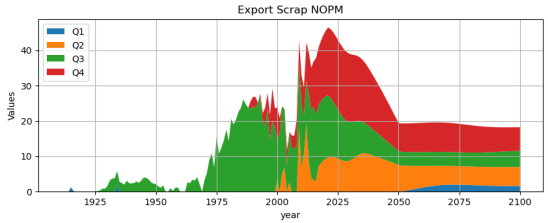
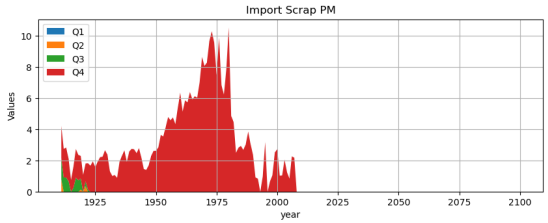
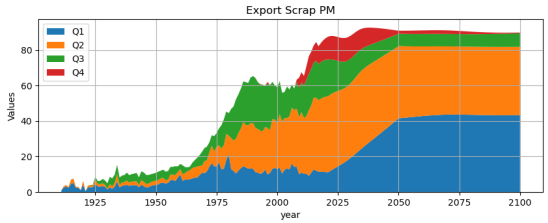
Q1
Q2
Q3
Q4
Values
year


Export Scrap NOPM
Q1
Q2
Q3
Q4
Values
year


Import Scrap PM
Q1
Q2
Q3
Q4
Values
year


Export Scrap PM
Q1
Q2
Q3
Q4
Values
year

F. Fabrication scrap per Intermediate and sector table

No.	*Steel semis*	*Buildings*	*Infrastructure*	*Cars*	*Trucks*	*Other Transport*	*Mechanical Engineering*	*Electrical Engineering*	*Other Metal Goods*	*Domestic appliances*	*Packaging*
7	Cast Steel						1		1		
8	Cast Iron	1	1	1	1	1	1	1	1		
9	Electrical Strip							0,8			
10	Tin plated										0,7
11	Plate	0,9	0,9	*0,8*		0,8	0,8	0,8	0,75		
12	Cold Rolled Coil galvanized	*0,9**	*0,9**	0,6	0,6		*0,74**	*0,8**	*0,74**	*0,8*	
13	Cold Rolled Coil coated	*0,9**	*0,9**	*0,6**	*0,74**		*0,74**	*0,8**	0,7	0,8	
14	Cold Rolled Coil	0,9	0,9	*0,6**	*0,74**		0,6	*0,8**	0,7	0,8	
15	Hot Rolled galvanized	0,9	0,9								
16	Hot Rolled Narrow Strip	0,9	0,9	*0,6**	*0,74**	*0,8**	*0,74**	*0,8**	0,75		
17	Hot Rolled Coil	0,9	0,9	*0,6**	0,8	*0,8**	0,8	0,8	0,75		
18	Welded Tube	0,95	0,95		0,95	0,95	0,95	0,95	0,95		
19	Seamless Tube	0,95	0,95	0,95	0,95	0,95	0,95	0,95	0,95		
20	Wire Rod	0,95	0,95	0,9	0,9	0,9	0,9	0,9	0,8		
21	Reinforcing Bar	0,95	0,95								
22	Hot Rolled Bar	0,9	0,9	0,8	0,8	0,8	0,8	0,8	0,7		
23	Heavy Section	0,95	0,95								
24	Light Section	0,95	0,95								
25	Rail Section		0,95				0,95				

G. Quality sector matrix

Quality assignment per sector based on average tramp element concentration adapted from Dworak et al., (2022).

Sector	*Assigned quality*
Transport	Q3
Industrial	Q3
Construction	Q3
Metal Goods	Q4
Metal good - packaging	Q1

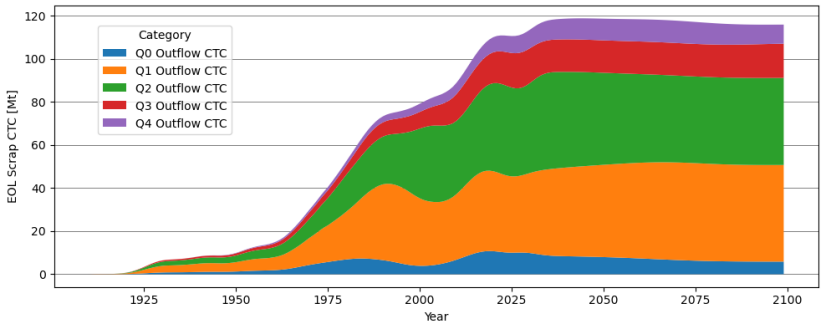
H. Scrap sorted in three ways.

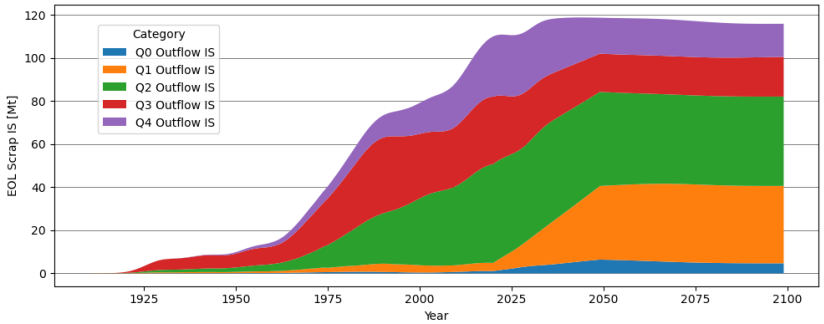
Graph showing the effect of sorting by category, sector or improving the sorting over time from 10% to 80% from 2017 to 2050 linearly.

CTC = category to category, every intermediate-sector combination is sorted according to the intermediate quality.

IS = improved sorting, changes over time.

STC = sector to category, every intermediate-sector combination is sorted according to the sector quality.


Category
Q0 Outflow CTC
Q1 Outflow CTC
Q2 Outflow CTC
Q3 Outflow CTC
Q4 Outflow CTC
EOL Scrap CTC [Mt]
Year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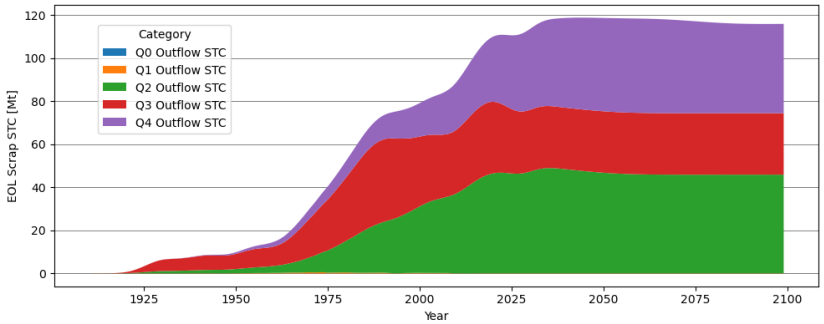
Q2 Outflow IS
Q3 Outflow IS
Q4 Outflow IS
EOL Scrap IS [Mt]
Year


Category
Q0 Outflow STC
Q1 Outflow STC
Q2 Outflow STC
Q3 Outflow STC
Q4 Outflow STC
EOL Scrap STC [Mt]
Year

I. Sensitivity Analysis

The main indicator to control the outcome of changing the parameters can be the MFA fit value for al Qs, describing the spread per parameter. So base scenario is S2 and then changing parameters showing the difference for each outcome.

Parameter change with 20% plus and 20% lower

- Demand
- Production scrap tolerance in steel qualities
- Production total scrap input in steel qualities
- EOL export of products
- Mix of EAF and BF-BOF for production
- Scrap sorting parameter 10-80%
- Stock in 1910
- Recovery rate Fab and production scrap
- Fab scrap factor
- Production scrap factor

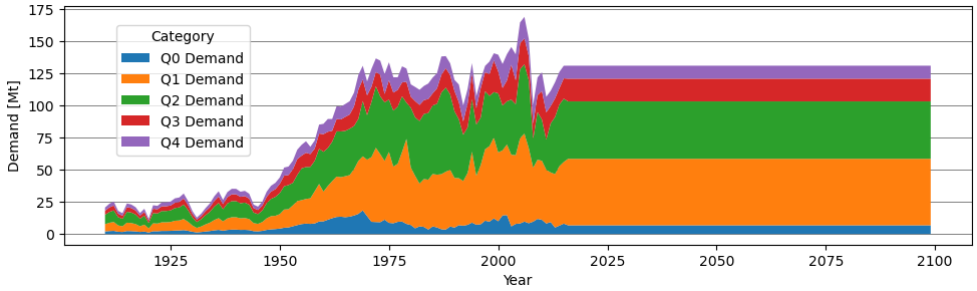
Inspiration can be taken from Dworak et all., (2022).

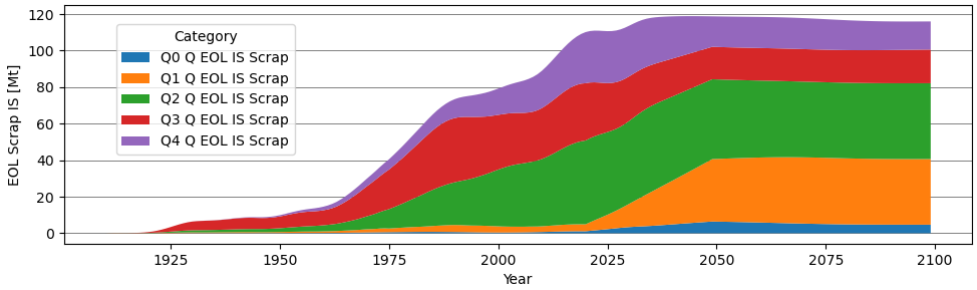
J. Plant data

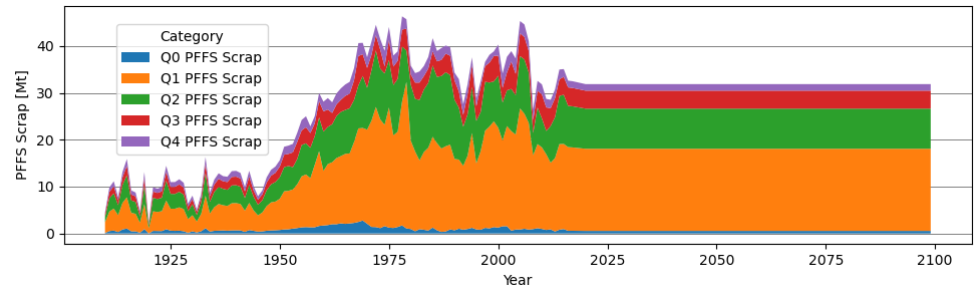
Batch_Quality	Average_Q1_Percentage	Average_Q2_Percentage	Average_Q3_Percentage	Average_Q4_Percentage	average_scrap_percentage_per_quality	counts
Q1	6,98	7,51	4,85	1,03	20,38	30792

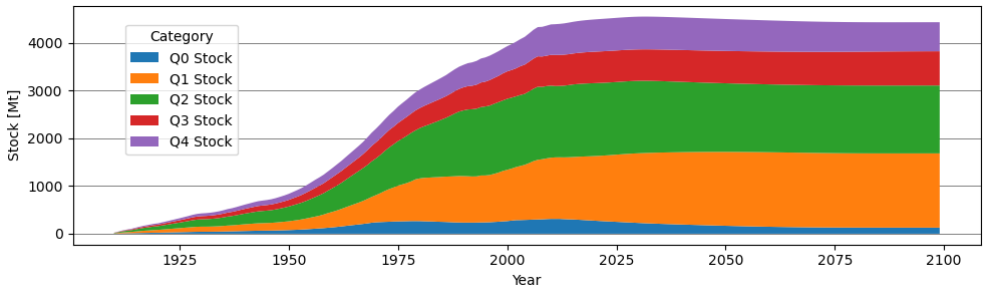
K. Scenario results of S1 and S2.

S1









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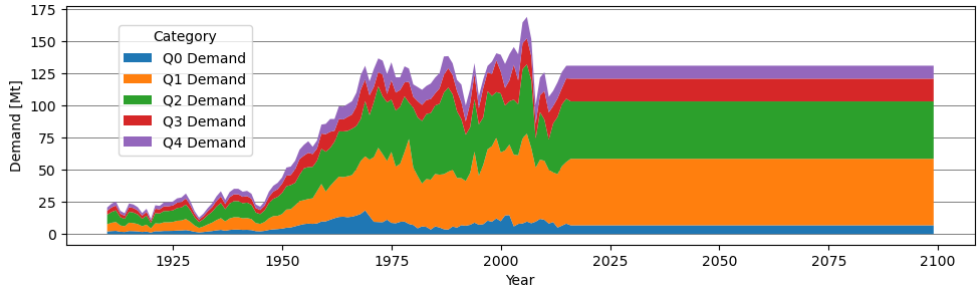
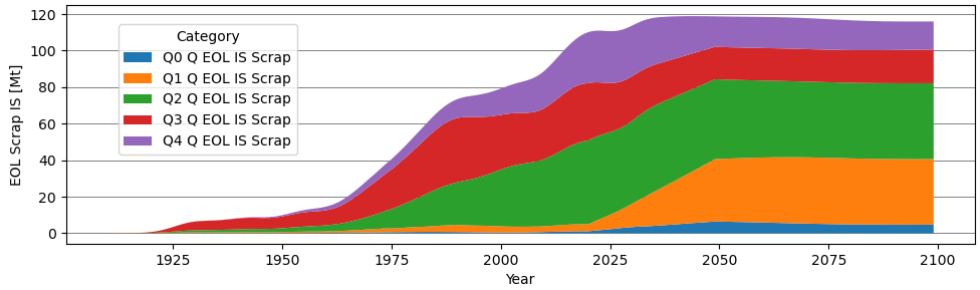
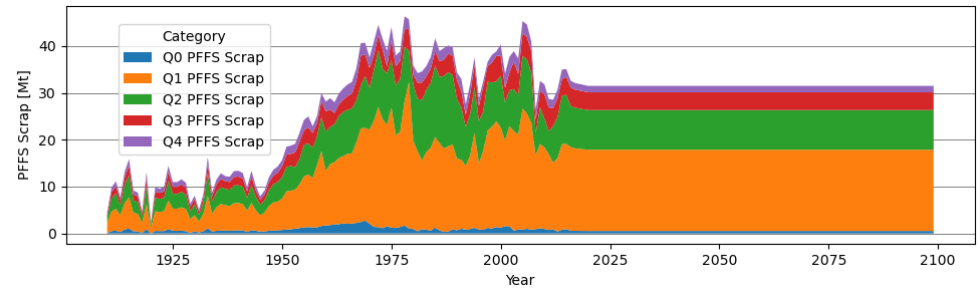
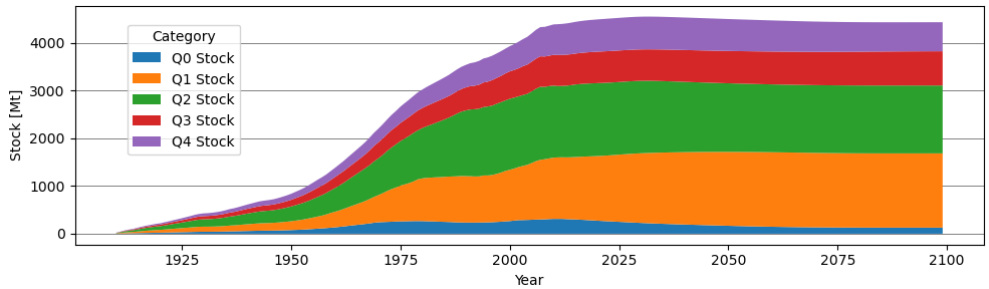
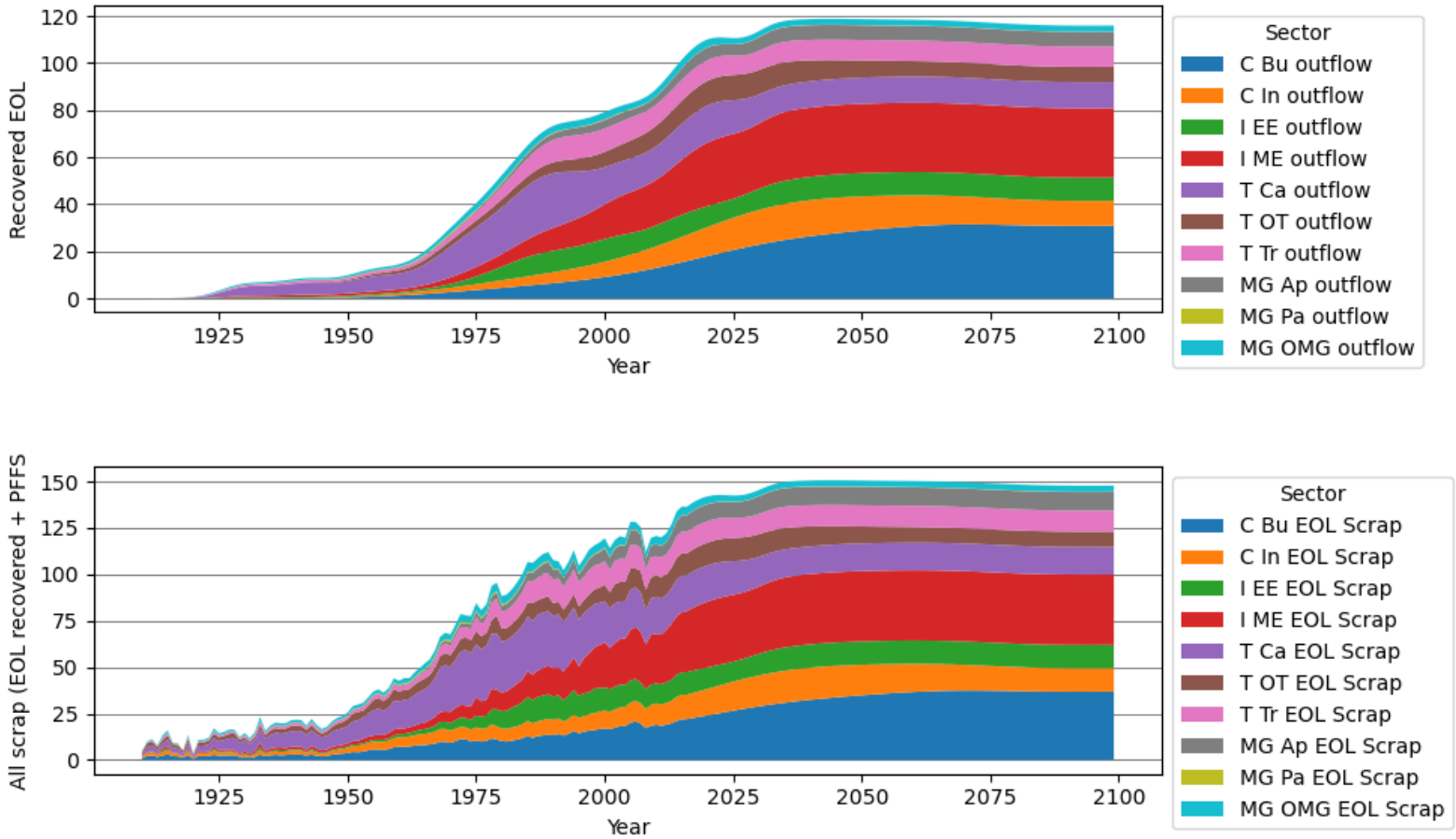


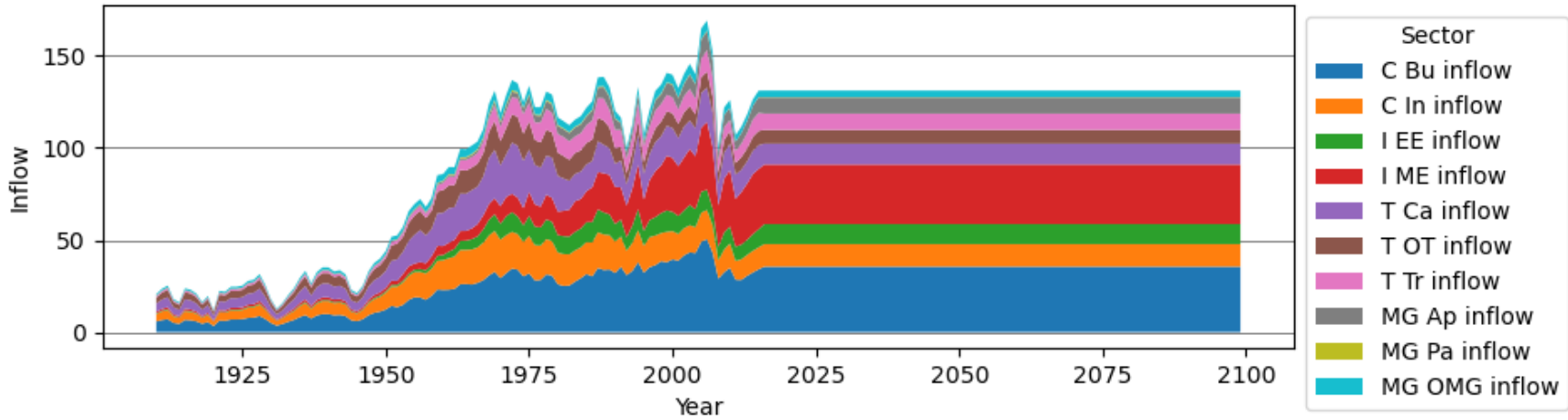


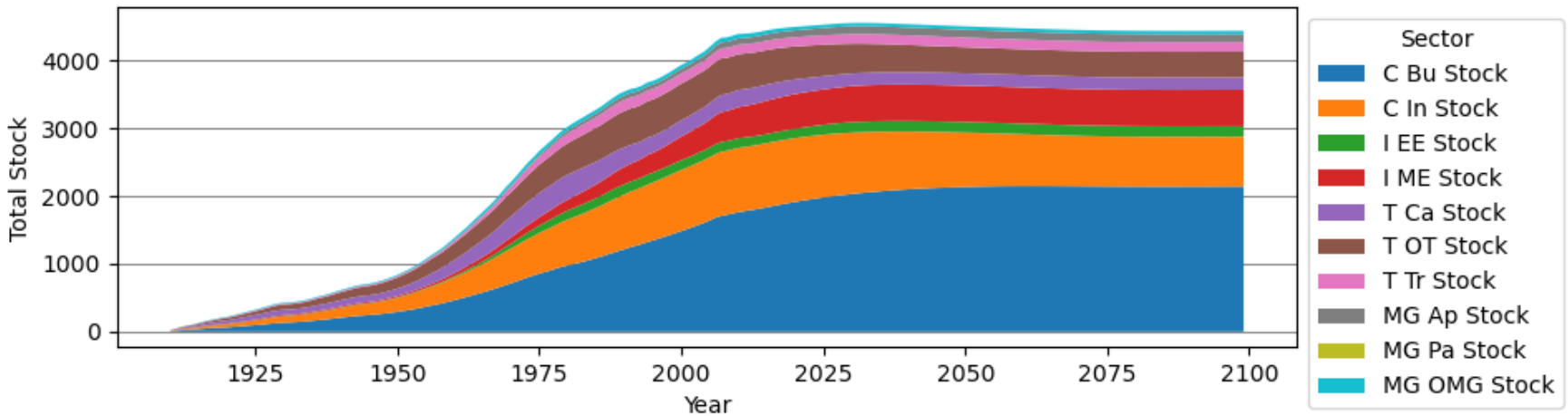




L. Metabolism steel by sector (scenario 1 results)




Inflow
150
100
50
0
1925
1950
1975
2000
2025
2050
2075
2100
Year
Sector
C Bu inflow
C In inflow
I EE inflow
I ME inflow
T Ca inflow
T OT inflow
T Tr inflow
MG Ap inflow
MG Pa inflow
MG OMG inflow

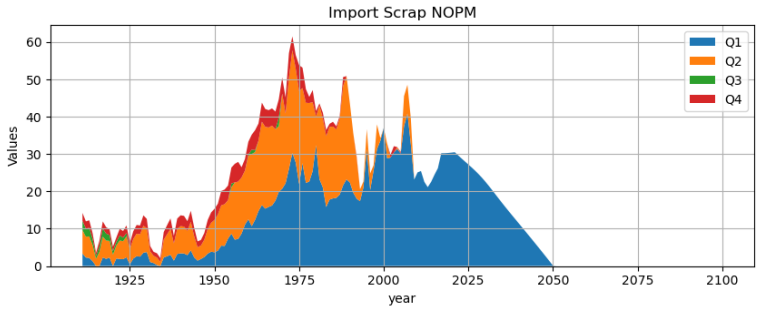

Total Stock
4000
3000
2000
1000
0
1925
1950
1975
2000
2025
2050
2075
2100
Year
Sector
C Bu Stock
C In Stock
I EE Stock
I ME Stock
T Ca Stock
T OT Stock
T Tr Stock
MG Ap Stock
MG Pa Stock
MG OMG Stock

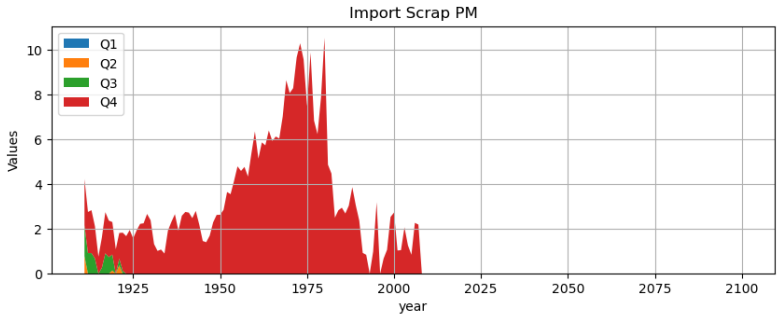
M. Import and export flows

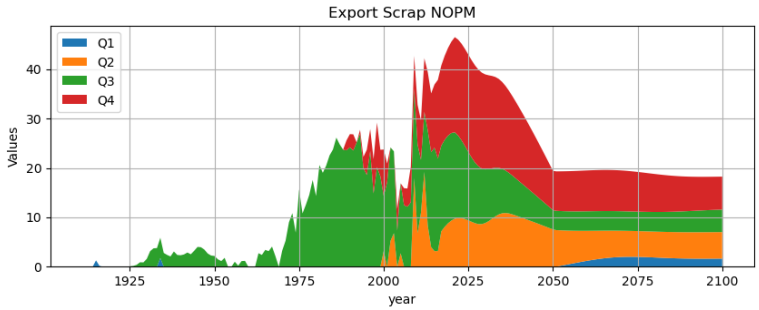
Scenario 1: Neto trade balance

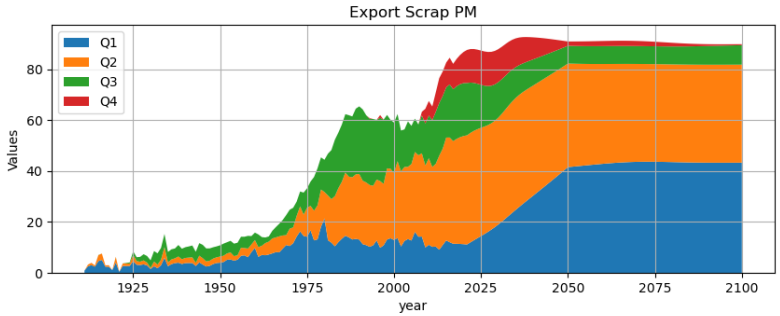
Title with NOPM means no production matrix in this analysis

Title with PM means that the production is used in the analysis.





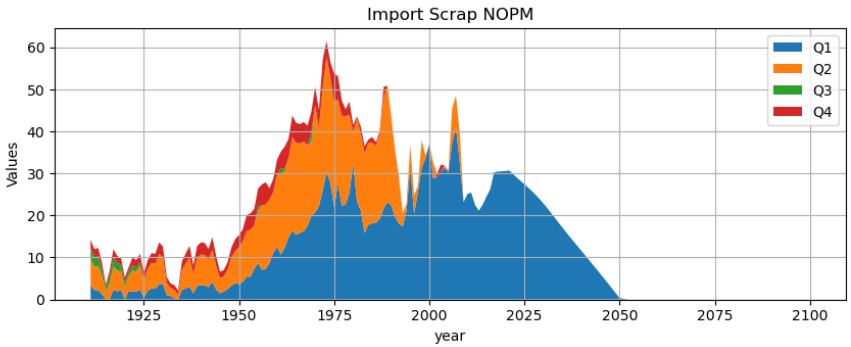


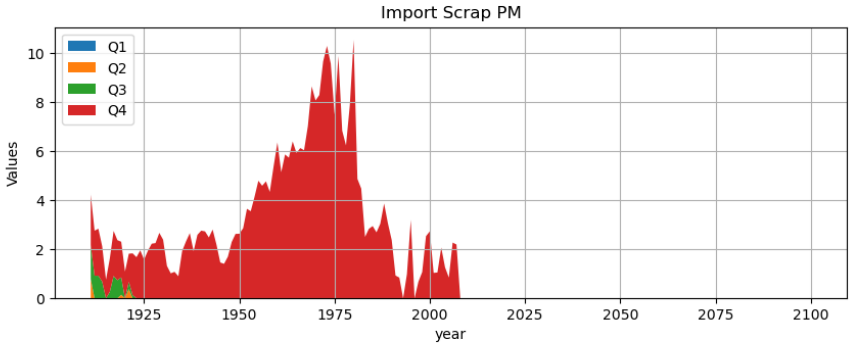


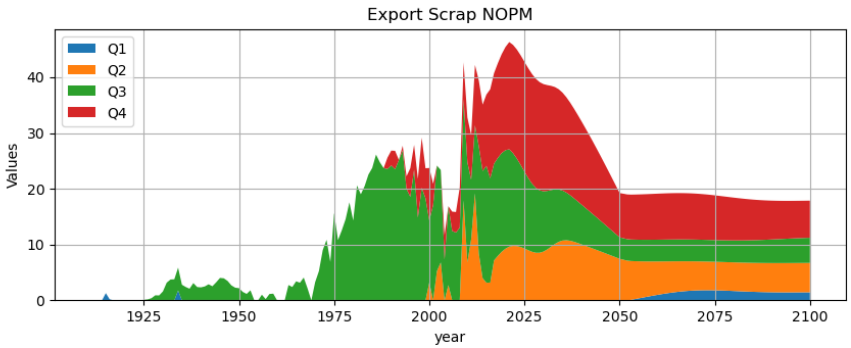
Scenario 2: business-as-usual

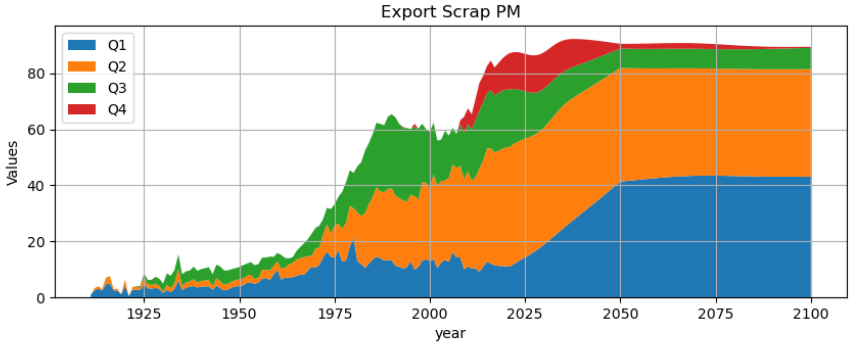
Title with NOPM means no production matrix in this analysis

Title with PM means that the production is used in the analysis.









Scenario 3: high trade deficit

Title with NOPM means no production matrix in this analysis

Title with PM means that the production is used in the analysis.