



Energy Systems Modelling Analytics Ltd

Modelling Zero Carbon Steel Manufacturing in the United States

Prof James GLYNN | ESMA, UG, LTU | SEAI-ETSAP

2026.10.07 | IETS ETSAP Joint online workshop | Galway, IRELAND



WHAT WE DO

ESMA Ltd. is a purpose driven company that builds innovative best-practice computer math models (LP/NLP/MIP) based on systems thinking, engineering, science, and ecological economics to create data-driven decision intelligence and logically navigate the uncertainty space to plan, invest, build, operate, and live within a sustainable, secure future energy system.

ESMA provides academically rigorous research consulting services on timescales that matter to decision makers, using best-in-class open energy systems models, leveraging the more than 50 years of institutional knowledge in the IEA-ETSAP TIMES open-source code to enable partnerships to co-create data-driven insights for optimal investment decisions, engineering operation, strategic long-term planning, policy uncertainty, and risk mitigation analytics in clean energy futures.

ESMA understands Trust and Relationships.

We incorporate community, city, national and global perspectives into our energy systems models, keeping the needs of the fair social good, community of practice, city, NGO, Government, finance and industry stakeholders in mind when considering our interconnectedness and dependencies.

Outline

- Recent Relevant Publications
- Why track mass balance as well as energy balance in ESOMs?
- Introduce OTUS
- Steel Reference Energy System
- Steel Future low carbon options “SubRES” (technology menu) in TIMES
- STEEL Topology DATA in OTUS
 - For your feedback and suggestions
- Some (H2 sensitive) preliminary results outlining method potential



Reference Material – Modelling Steel



Energy Policy

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Technology and policy options for achieving net zero steel manufacturing in the United States

Francis G.N. Li ^a, Chris Bataille ^b, Seton Stiebert ^c, Taiba Jafari ^b, Olexandr Balyk ^b, James Glynn ^b [Show more](#)

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Highlights

- First spatial model of global steel transition across 137 countries.
- U.S. net-zero steel achievable by 2050 using existing technologies.
- Clean steel deployment is highly sensitive to U.S. trade policy design.
- 2025 U.S. steel tariffs validate modeled high-tariff scenario.
- Trade blocs like USMCA can enable faster, lower-cost decarbonization.

Abstract

This paper explores strategies for achieving net zero emissions in the United States steel industry by 2050, consistent with the Paris Agreement. The US faces a pivotal moment in the lifecycle of its steel production fleet in the late 2020s, where the opportunity exists to integrate next generation clean steel technologies into the industrial base and become a global market leader in net zero steel by mid-century. Effective policy support at the federal and state levels will be essential for transitioning the most GHG-intensive production methods to cleaner alternatives during this upcoming window of opportunity. Our results indicate that the Inflation Reduction Act alone is unlikely to be sufficient to drive a timely transition to net-zero steel production, and that additional demand-side, trade-related, and post-IRA policy measures are required. The paper contextualizes U.S. steel production within global efforts, examining implications for technological change, energy demand, emissions reductions, and international trade using a geospatially detailed techno-economic model of steel production across 137 countries and 1000+ facility locations. Our analysis finds that the US is well positioned to be one of the first countries in the world to achieve net zero steel manufacturing and could make this transition using existing technologies, but the speed of transition and the resulting patterns of investment are sensitive to US policy choices on trade openness to the rest of the world and with close allies. Trade-restrictive pathways, while capable of accelerating domestic decarbonization, also entail higher costs and economic risks that must be carefully managed.

Article preview

[Abstract](#)
[Introduction](#)
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Applied Energy

Date: 15 September 2021

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Volume: Volume 298

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Decarbonizing China's iron and steel industry from the supply and demand sides for carbon neutrality

Ming Ren ^a, Pantao Lu ^a, Xiaorui Liu ^a, M.S. Hossain ^a, Yanru Fang ^a, Tatsuya Hanooka ^b, Brian O'Gallochir ^{c,d}, James Glynn ^a, Hancheng Dai ^a

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Highlights

- An integrated top-down and bottom-up modeling framework was developed.
- Analyze low-carbon pathways for Chinese iron & steel industry towards carbon neutrality.
- Both the supply-side and demand-side contributions to decarbonization are explored.
- Energy-saving retrofitting technologies help short-term CO₂ emissions reduction.
- Breakthrough technologies are crucial in achieving carbon neutrality.

Article preview

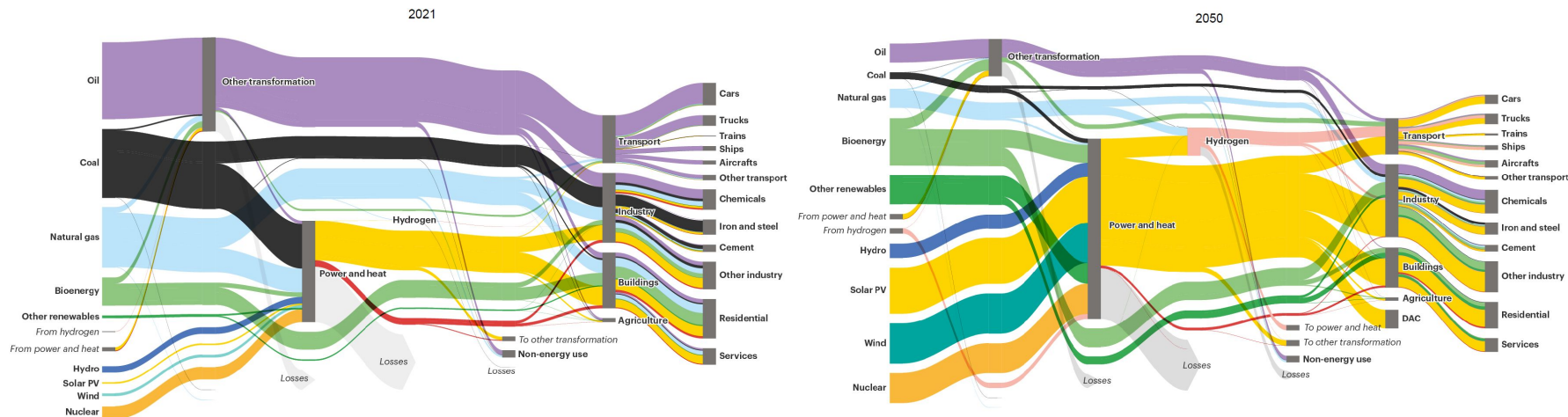
[Abstract](#)
[Introduction](#)
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[References \(54\)](#)

Abstract

Iron and steel production in China contributes to 14% of China's total energy-related CO₂ emissions. Decarbonizing the iron and steel sector will therefore play an important role in achieving the goal of carbon neutrality. This study explored possible low-carbon transition pathways for China's iron and steel industry to achieve carbon neutrality by 2050. An integrated approach was developed that combined a computable general equilibrium

- Co-Authors & Co-developers of Steel in TUSM | Francis Li, Chris Bataille, Seton Stiebert, Taiba Jafari, Olexandr Balyk

Fossil Fuel and Future NZ Energy Flows

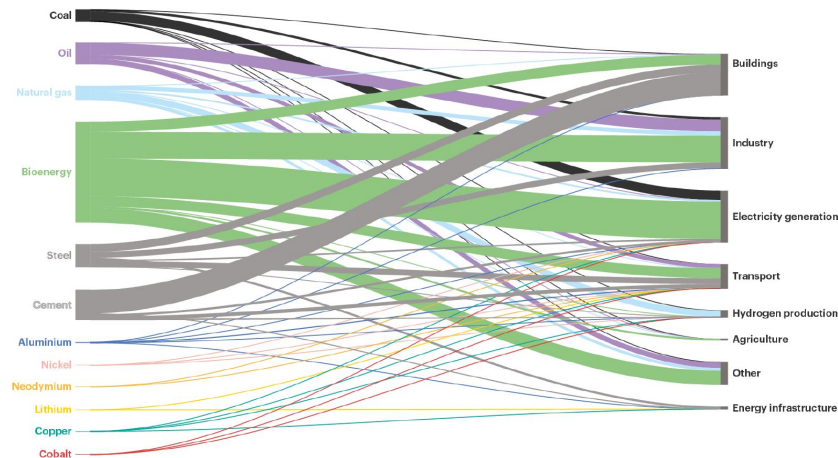
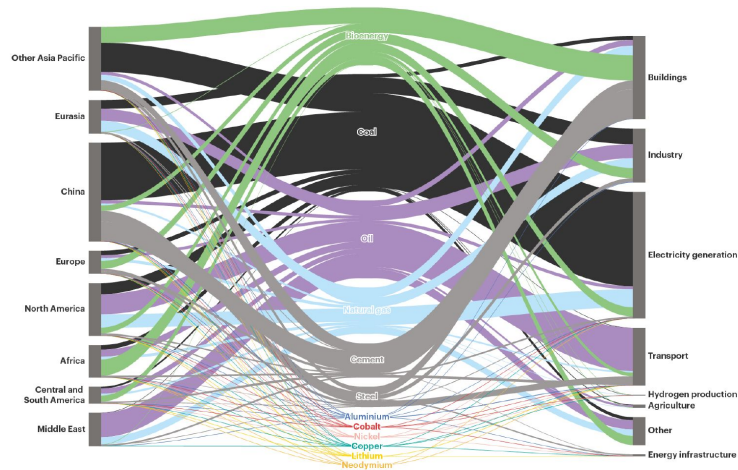


Source: IEA, 2023, *Energy Technology Perspectives*

IEA, CC BY 4.0.

- Despite the rapid recent growth in clean energy technologies and demand for metals critical to them, the world still relies primarily on coal, oil and gas to meet its energy needs
- Electricity becomes the largest energy vector in the NZE scenario, with demand more than doubling between 2021 and 2050.

Fossil Fuel Flows to Material Stocks



IEA. CC BY 4.0

IEA. CC BY 4.0

Source: IEA, 2023, *Energy Technology Perspectives*

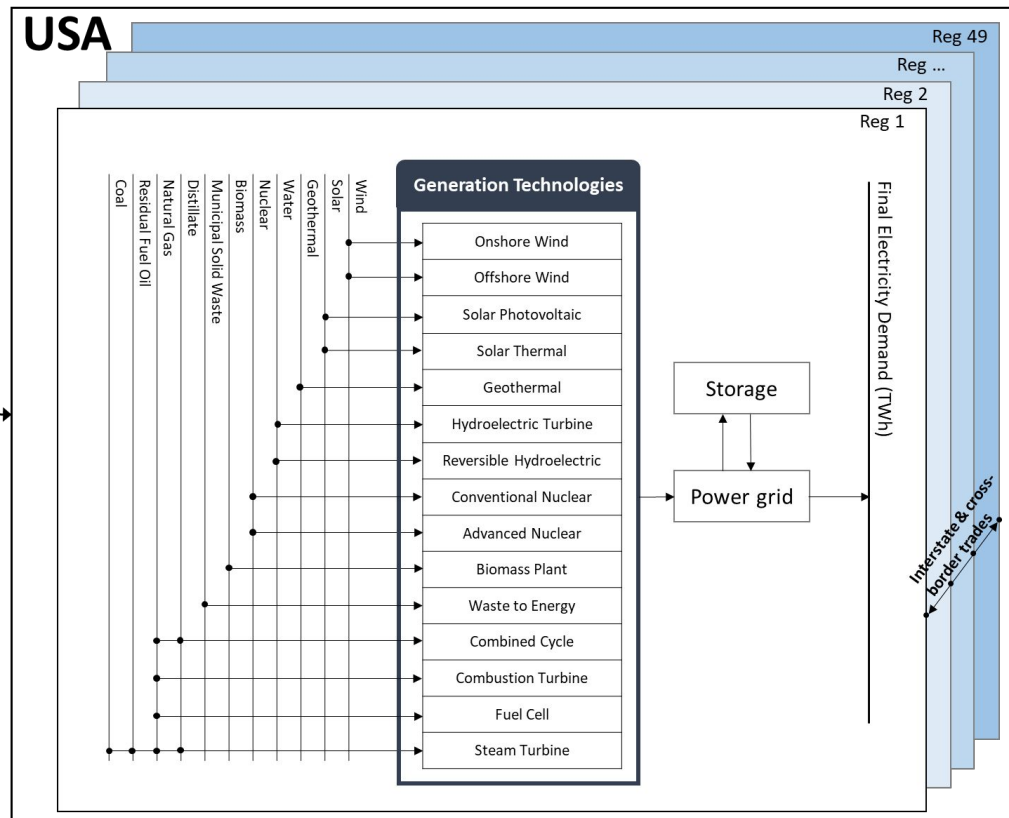
- Despite the rapid recent growth in clean energy technologies and demand for metals critical to them, the world still relies primarily on coal, oil, gas, biomass, cement and steel, in terms of mass (kg) to meet component needs.
- The mass of resources used in the energy system in 2050 in the NZE scenario is about half that of today. Coal, Oil and Gas collapse. Materials account for about one third of inputs in 2050. Mining volumes thus change dramatically
- Included Material Mass Balances important for Critical Materials and Circularity like Steel, Scrap, Recycling etc.

Open TIMES US Topology Schema

- Input Data

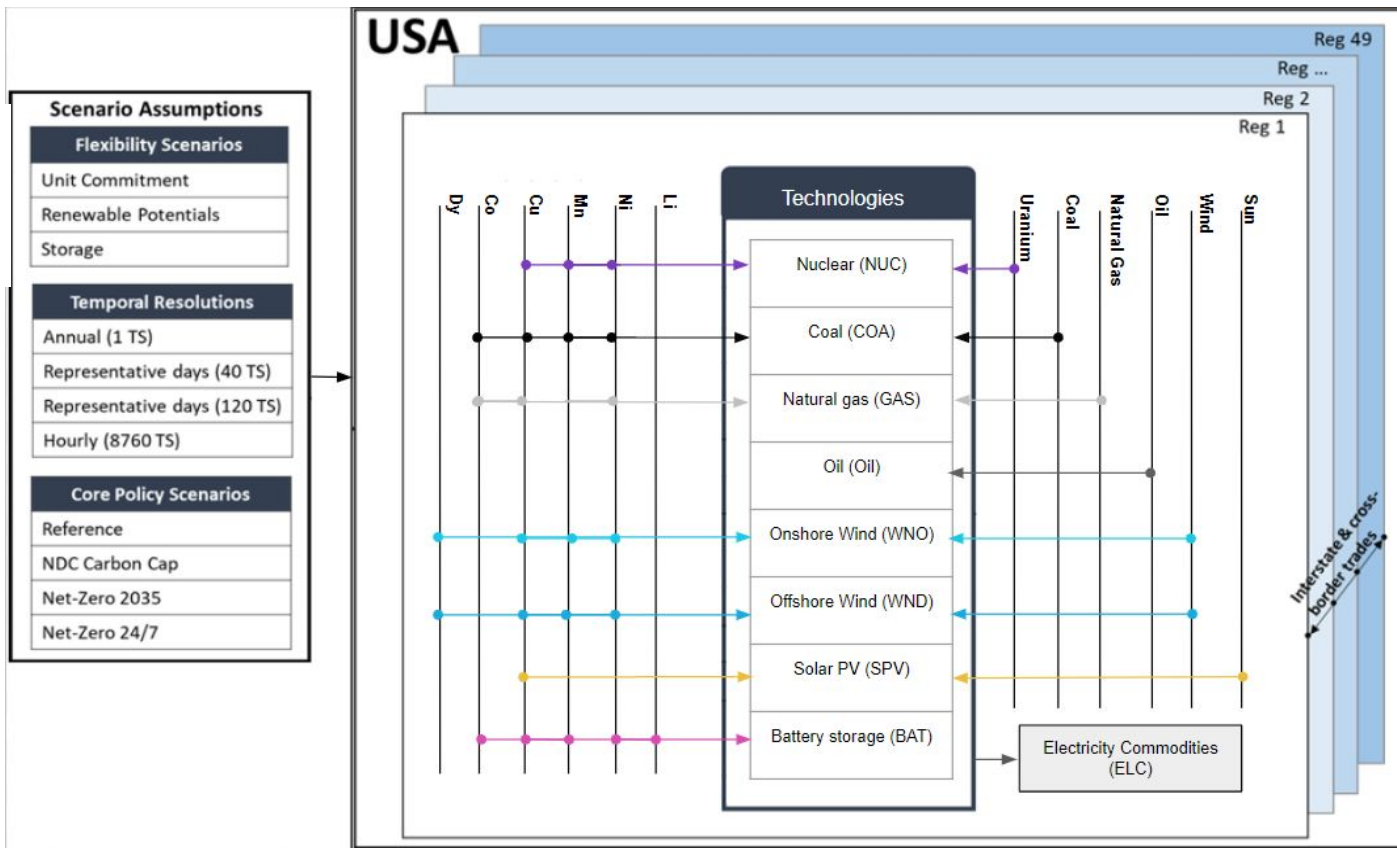


Scenario Assumptions	
Flexibility Scenarios	
Unit Commitment	
Renewable Potentials	
Storage	
Temporal Resolutions	
Annual (1 TS)	
Representative days (40 TS)	
Representative days (120 TS)	
Hourly (8760 TS)	
Core Policy Scenarios	
Reference	
NDC Carbon Cap	
Net-Zero 2035	
Net-Zero 24/7	



Including Critical Mass Balances

- Input Data

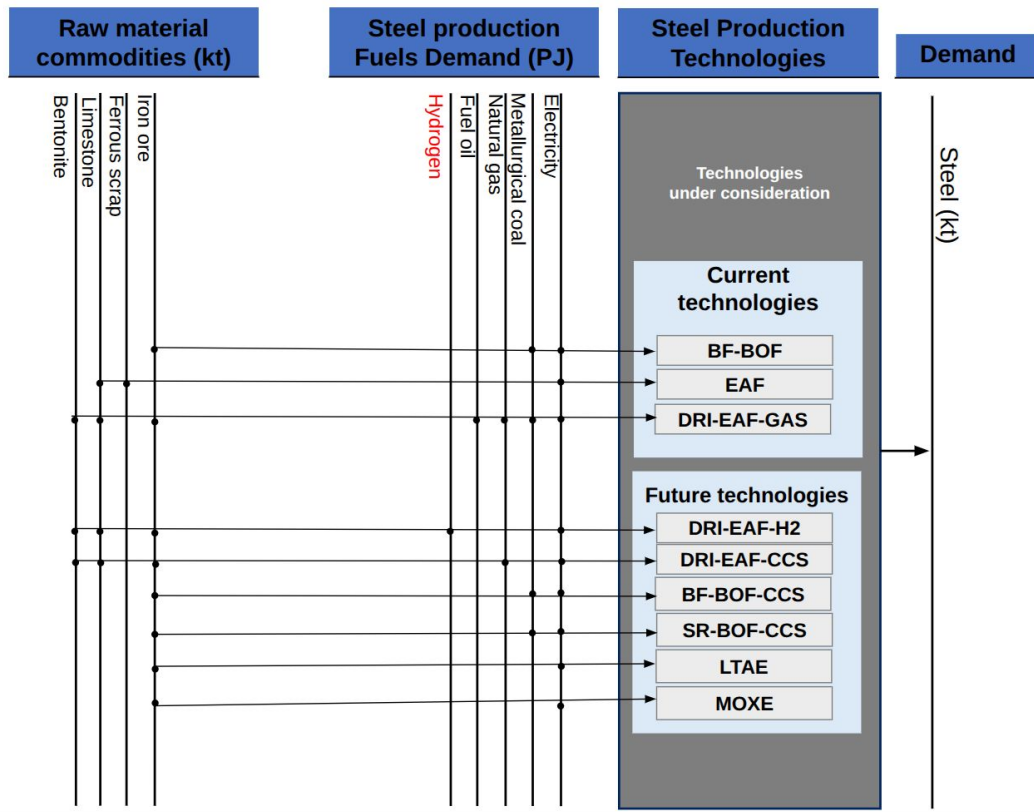


Including Steel Mass Balances in OTUS

- Input Data



Global
Energy
Monitor



Current Steel Mill Stock & Capacity

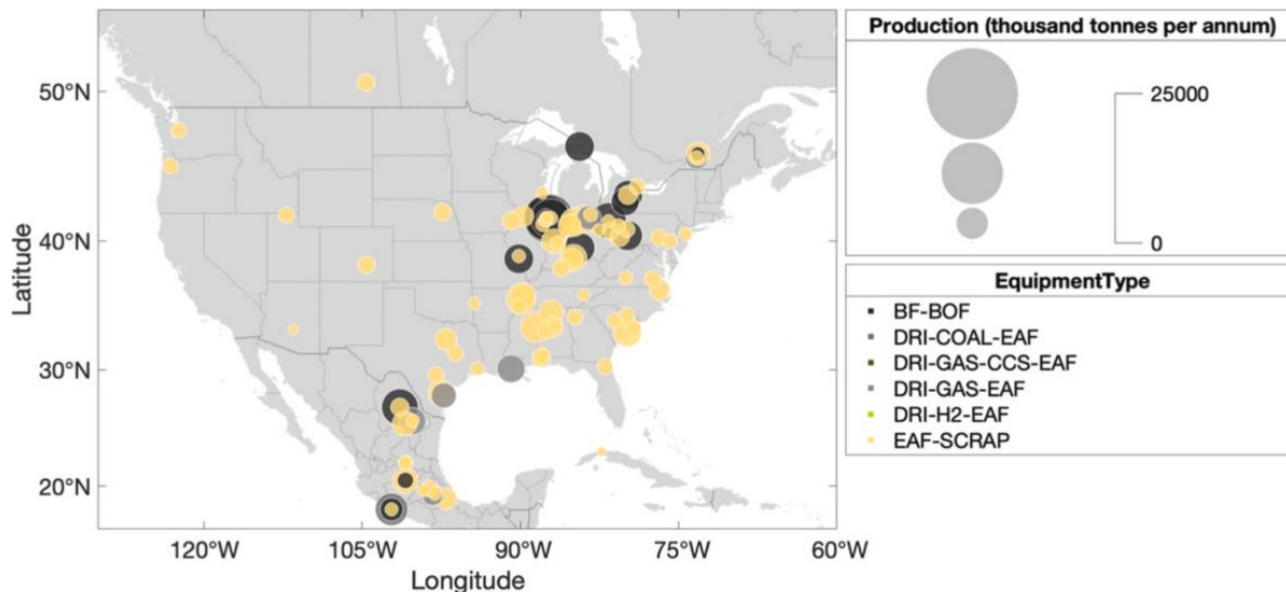


Fig. 3. – Spatial distribution of steel production in the continental US, 2021

- Current Mill Stock
 - Largely BF-BOF & EAF-Scrap recycling with some DRI-EAF

Reference: Li, Francis GN, Chris Bataille, Seton Stiebert, Taiba Jafari, Olexandr Balyk, and James Glynn. "Technology and policy options for achieving net zero steel manufacturing in the United States." Energy Policy 211 (2026): 115124. <https://doi.org/10.1016/j.enpol.2026.115124>

- Data Sources:
 - Global Energy Monitor (GEM)
 - NZ Steel Project (Chris Bataille & Francis Li)
- Declare current Mill Stock by technology type by state by capacity by year
 - https://github.com/esma-ie/OTUS/blob/main/VT_US_IND_IIS.xlsx
- Future Steel demand per state per year based on per capita per GDP trends.

#VALUE!					
Sets	Region	TechName	TechDesc	Tact	Tcap
* Technology Description					
DMD		IND_EAF	Electric Arc Furnace	Mt	Mta
DMD		IND_BF_BOF	Basic Oxygen Furnace	Mt	Mta
DMD		IND_DRI_EAF	Direct Reduced Iron	Mt	Mta
DMD		IND_DRI-EAF-H2	IND_DRI-EAF-H2	Mt	Mta
MIN		MINSCR	Scrap supply	Mt	Mta
MIN		MINIRO	Iron ore supply	Mt	Mta
MIN		MINLIM	Limestone supply	Mt	Mta
IMP		IMPIIS	Steel import	Mt	Mta
IMP		IMPH2	Hydrogen import	PJ	PJa
IMP		IMPBEN	Bentonite import	Mt	Mta
PRE		SCA-INDELC	Industry electricity supply	PJ	PJa
PRE		SCA-INDCOA	Industry coal supply	PJ	PJa
PRE		SCA-INDRFO	Industry residual fuel oil supply	PJ	PJa
PRE		SCA-INDNGA	Industry natural gas supply	PJ	PJa

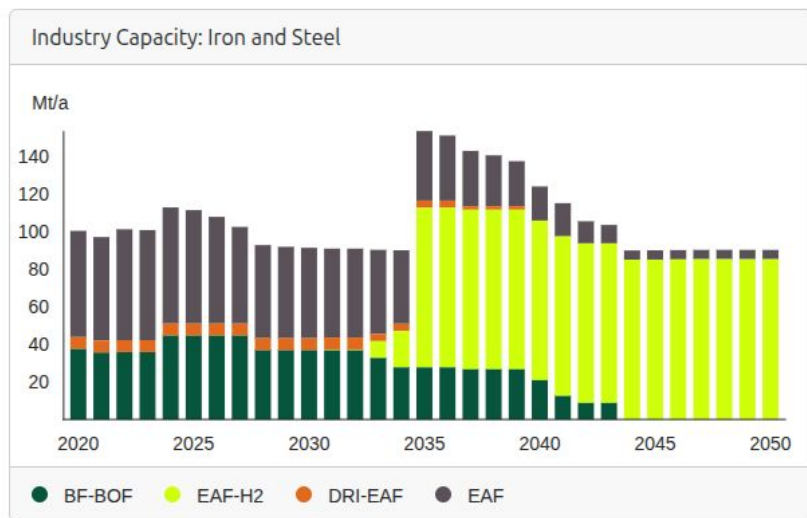
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Future Steel Technologies – SubRES

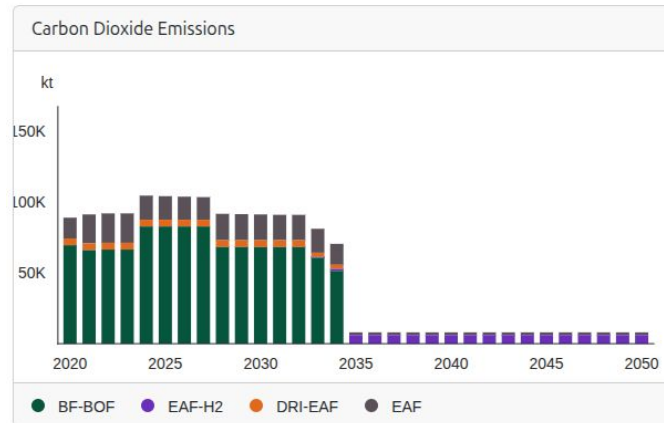
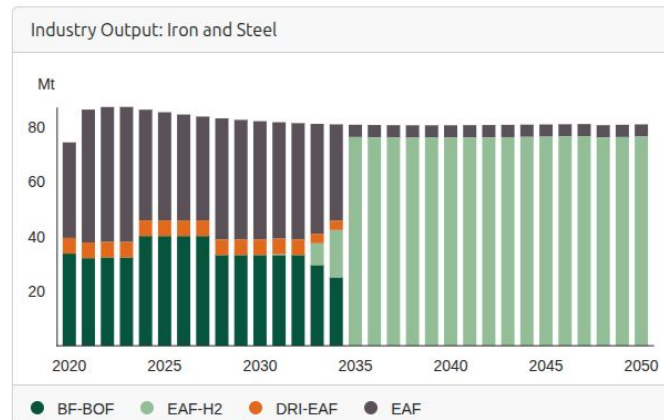
~FI_Process														
Sets		TechName		TechDesc									Tact	Tcap
\I: Process Set Membership		Technology name		Description									Activity unit	Capacity unit
NRG		IIS_BF_BOF		Blast Furnace - Basic Oxygen Furnace									kt	kt
NRG		IIS_EAF		Electric Arc Furnace									kt	kt
NRG		IIS_DRI-EAF-GAS		Direct Reduced Iron (using natural gas) with Electric Arc Furnace									kt	kt
NRG		IIS_DRI-EAF-H2		Direct Reduced Iron (using hydrogen) with Electric Arc Furnace									kt	kt
NRG		IIS_DRI-EAF-GAS-CCS		Direct Reduced Iron (using natural gas) with Electric Arc Furnace and with Carbon Capture and Storage									kt	kt
NRG		IIS_BF-BOF-CCS		Blast Furnace - Basic Oxygen Furnace with Carbon Capture and Storage									kt	kt
NRG		IIS_SR-BOF-CCS		Smelting Reduction - Basic Oxygen Furnace with Carbon Capture and Storage									kt	kt
NRG		IIS_LTAE		Low Temperature Alkaline Electrolysis									kt	kt
NRG		IIS_MOXE		Molten Oxide Electrolysis									kt	kt
~FI_T														
TechName	*TechDesc	Comm-IN	Comm-OUT	Start	NCAP_ILED	INVCOST	VAROM	FIXOM	EFF	Other_In LIFE	Cap2Act	AF	ENVACT	
\I: Technology Name	Technology Description	Input Commodity	Output Commodity		Lead time between investment decision	Overnight investment cost (USD 2022/tonne steel) [INVCOST]	Variable O&M (USD 2020/tonne steel) [VAROM]	Fixed O&M (USD 2020/ton steel) [FIXOM]	Energy intensity (MWh/ton steel) [EFF]	Technical life		Max. capacity factor	Carbon intensity (ton CO2e/ktonne steel) [ENVACT]	
IIS_BF_BOF	Blast Furnace - Basic Oxygen Furnace	IIS_COA	IIS	1952		721.4	268.1	85	5.49	25		0.9	1788.26	
IIS_EAF	Electric Arc Furnace	IIS_ELC	IIS	1905		581.8	311.2	91	0.63	25		0.9	242.97	
IIS_DRI-EAF-GAS	Direct Reduced Iron (using natural gas) wi	IIS_NGA	IIS	1970		1047.2	228.1	112	4.03	25		0.9	807.97	
IIS_DRI-EAF-H2	Direct Reduced Iron (using hydrogen) with IIS_H2	IIS_H2	IIS	2030		1407.9	557.1	118	3.64	25		0.9	80.00	
IIS_DRI-EAF-GAS-CCS	Direct Reduced Iron (using natural gas) wi IIS_NGA	IIS_NGA	IIS	2016		1186.8	244.4	145.8	5.05	25		0.9	301.03	
IIS_BF-BOF-CCS	Blast Furnace - Basic Oxygen Furnace with IIS_COA	IIS_COA	IIS	2030		989.0	294.2	138.8	7.08	25		0.9	304.31	
IIS_SR-BOF-CCS	Smelting Reduction - Basic Oxygen Furnace IIS_COA	IIS_COA	IIS	2028		954.1	298.7	138.8	9.55	25		0.9	335.92	
IIS_LTAE	Low Temperature Alkaline Electrolysis	IIS_ELC	IIS	2040		1102.6	377.5	82.92025	3.60	25		0.9	1399.51	
IIS_MOXE	Molten Oxide Electrolysis	IIS_ELC	IIS	2040		1003.0	377.8	98.7861	3.70	25		0.9	1438.39	

Source: https://github.com/esma-ie/OTUS/tree/main/SubRES_Tmp1

NZE2035; Preliminary Work from 2023



- Preliminary Results – for method illustration only – Please Don't Cite
- BASE Scenario and NZE 2035 scenario from IRA, ran in 2023.
- EAF-H2 growth in early 2030s squeezes out BF-BOF & EAF in late 2030s early 2040s
 - Sensitive to H2 Price, which in turn is sensitive to REnewables operations.
- This work is paused at the moment



Wrap Up

- What are the benefits of endogenizing mass balances and materials flows within TIMES?
 - Endogenizing Trade constraints on manufacturing outcomes in NZE scenarios
 - Endogenizing speed of construction based on material availability
 - Endogenizing construction time (iLED) based on material availability and cost.
- Track Material types through regions
 - Zero carbon Steel – Carbon Border Adjustment Mechanism
 - Incentives, environmental conservation and protectionism
 - Track co-dependencies on energy flows, material stocks and flows and environmental emissions
 - Track cost of geopolitical tensions
 - Track costs of trade policies
 - Track embodied emissions in materials and steel
- Endogenizing retrofit options critical given the lifespan of steel mills
 - Can be refurbished indefinitely.
 - eLife & tLife can be readily extended and switched soon to lower carbon options

Thank you for your time and attention.



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