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Techno-economic optimisation of steel supply chains in the clean energy transition: A case study of post-war Ukraine

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ABSTRACT

The steel industry's clean energy transition can enable new market creation and economic growth stimulation. Yet, the most efficient and feasible pathway to decouple the sector from fossil fuels remains unclear, particularly within developing nations and unstable socio-political contexts. Here, a blueprint for reconfiguring plant locations and reallocating resources is developed through a Ukrainian case study under two scenarios, which capture potential post-war conditions. Framed by regrowth of Ukraine's export-oriented steel industry and prospective European Union accession, green iron and steel trade strategies are devised. A steel supply chain optimisation model underpins the techno-economic, spatially granular analysis of energy and material flows, which utilises the inputs from a separate cost-minimised renewable energy, green hydrogen, and green ammonia production model. Results show that optimal supply chain configurations rely on mixed emissions-free energy profiles, the emergence of new steelmaking sites nearby high-quality renewables, regional alliances for green iron and steel market creation, and multi-billion-dollar investment. Mature nuclear and hydro power critically reduce costs in the near-term, whilst the rapid expansion of solar and wind energy infrastructure underpins production system scale-up. To simultaneously rebuild the 22 million-tonnes-a-year Ukrainian steel industry and transition to near-zero emissions by 2050, infrastructure investment surmounts to $62 billion, given full liberation of Ukrainian territory. Near-term investment is necessary to ease the pace of change, and although mobilising capital of this magnitude will be challenging, convincing carbon prices favour decarbonisation efforts.

1. Introduction

On February 24, 2022, Russia invaded Ukraine, in a major escalation of the existing Russo-Ukrainian war, which began in 2014 with the annexation of Crimea (Biersack and O'Lear, 2014; European Union, 2022a). Ukraine's steel industry has been severely affected by the Russian invasion, with deliberate attacks on industrial assets and transport routes, as well as the seizure of hydrocarbon resources in the Donbas region in the east, and the Black Sea-Sea of Azov areas in the south (Mykhnenko, 2020). Whilst the war endures, plans have been developed for Ukraine's post-war recovery to restore stability and stimulate economic growth, with a Ukraine Development Fund to mobilise private capital into key sectors (BlackRock, 2023). Rebuilding the country's steel sector could include a transition to near-zero emissions. This recovery pathway could potentially be economically competitive with the right investment timing and selection of technologies.

Ukraine's export-oriented steel industry is fundamental to the national economy; though, it is deeply dependent on fossil fuels. The steel sector has remained the second largest employer within manufacturing, with average monthly nominal wages being 15% higher than the national average (Ukrstat, 2022). In 2021 (pre-invasion), the steel sector (including 'Basic metals' and 'Fabricated metal products' industries) accounted for 2.3% of Ukraine's Gross Domestic Product (GDP) and 14.5% of Ukraine's industrial output, with steel companies selling $16bn worth of basic metals abroad, and paying $3.5bn in taxes to the

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State budget (Boyko, 2022). Yet, Ukrainian steel production emits copious amounts of greenhouse gases; in 2020, the nation produced 20.6 million tonnes (Mt) of crude steel, causing 48 Mt CO_2, which was equivalent to 15% of national emissions (318 Mt CO_2; MEPR, 2023). The nation produces some of the world's most emissions-intensive steel at 2.3 tonnes of CO_2 per tonne of steel (CO_2/t steel) on average – *the worst* ranking of the 17 studied nations/regions (Hasanbeigi, 2022). There is deep dependence on coal-based blast furnaces (BF), and ongoing use of outdated open-hearth furnaces (OHF), which have been substituted widely by the more efficient basic oxygen furnace (BOF). Of Ukraine's total pre-war steel production, 76% stemmed from the BF-BOF route, 19% from the BF–OHF route, and 6% from the electric arc furnace (EAF) route (World Steel, 2021). The average emissions-intensity for the BF route was 2.41 t CO_2/t steel (Metinvest, 2020), and for the EAF route 0.77 t CO_2/t steel (Interpipe, 2021).

Green steel could offer a practical way forward towards the long-term climate neutrality goal that revitalises economic activities and supports Ukraine's security aims. Green steel could emerge as an export and investment catalyst, necessitating focused investment in adaptable and innovative production capacities (Gorodnichenko and Sologoub, 2022). Furthermore, clean industry investment will support stronger long-term economic and environmental outcomes by creating new green jobs, whilst decreasing CO_2 emissions (Zagoruichyk et al., 2023) – especially important as unemployment rates have soared to 25% during the war (NBU, 2023). The economic case for Ukraine using renewables in steel production is underpinned further by the European Union (EU) membership requirements. Attaining membership in the EU will aid in economic resilience and trade integrity as Ukrainian-EU supply chains converge. In the event of Ukraine's accession to the EU, the country will become subject to the regulatory framework of the Emission Trading Scheme (ETS), wherein the carbon price, as of August 2023, is established at around \$100/t CO_2 (Ember, 2023) and is forecast to increase to \$250/t by 2050, without any free allowances (IEA, 2022). The 'EU Green Deal' targets commercialisation of near-zero emissions steel by 2030, and full decarbonisation of the sector by 2050 (EC, 2023). Consequently, Ukraine must prepare for this impending transition. This study comprehensively addresses the knowledge gap on how to strategise the development of efficient and competitive green steel supply chains, underpinned by strategic regional trade partnerships.

After briefly charting the existing literature on decarbonised steel production technologies and their supply chain configurations, this paper presents the steel supply chain optimisation model, and connecting renewable energy (RE) optimisation model, as well as other core components of the methodology. All potential transitions depend on how the war evolves; hence, this pioneering research is framed within two scenarios with distinct geopolitical and natural resource constraints. Following, results are presented and discussed, and relevant conclusions drawn for policymakers, investors, and steelmakers to support the green industrial transition concerned.

2. Literature review

2.1. Steel decarbonisation options

This study follows a deep decarbonisation framework to assess the economic viability of Ukraine's green steel transition. Ironmaking - where reduction of iron ore to metallic iron and, therefore, most emissions occur - precedes steelmaking - where alloying elements are added to the mix and impurities removed via slag. The ironmaking process can be eliminated for scrap-based EAF production. However, since scrap supply is globally constrained, being in especially low supply in developing nations (Wang et al., 2021), enhancing material recyclability will support, but not solve, the steel sector's decarbonisation challenge. Therefore, transformative deep decarbonisation technology for ore-based production is needed to shift the industry onto a near-zero emissions trajectory. If fossil fuels are completely removed from the process as ore reductants and thermal energy inputs, a minor amount of carbon must be added during steelmaking (steel is an alloy of iron and carbon), producing a small amount of CO_2, alongside the CO_2 produced from the graphite electrodes in electric smelting operations, which total less than 5% of BF-BOF emissions (Vogl et al., 2018). Although there is no universal definition of green steel (Hasanbeigi & Sibal, 2023), the International Energy Agency proposed a quantitative threshold for near-zero emissions production of less than 0.4 t of CO_2 equivalent (CO_2e) per tonne (CO_2e/t) of steel for 100% ore-based production, reducing linearly to 0.05 t CO_2e/t steel for 100% scrap-based production (IEA, 2022). Subsequently, 'green steel' is defined in this work as *steel produced in the (near full) absence of fossil fuels*, used interchangeably with 'near-zero emissions steel'. This definition is extended to 'green' hot briquetted iron (HBI), the intermediary product between direct reduction ironmaking and steelmaking.

A variety of technologies within the steel production process can reduce industrial emissions. Three key deep decarbonisation pathways lead sectoral innovation of ore-based production: (1) green hydrogen-based direct reduction of iron (followed by EAF steelmaking; also known as H_2-DRI-EAF), (2) direct iron electrolysis (followed by EAF steelmaking), and (3) carbon capture, utilisation, and storage (CCUS), retrofitted to integrated BF-BOF facilities (Fan and Friedmann, 2021). Considering the dominance of BF assets in Ukraine, H_2 injection, top gas recycling, and bio-carbon integration could also be useful; though, all offer only partial emissions reductions. Computational modelling has shown the maximum H_2 injection rate to be 28 kg/t with 12 vol% oxygen enrichment, which can reduce CO_2 emissions by 18% (Shatokha, 2022). CCUS has limited effectiveness, due to the multiplicity of flue gases in a BF-BOF facility, and is not yet proven at industrial scale. Simultaneous CO_2 capture from BF, power plant, and hot stove gases could reduce total plant emissions by 80%; however, costs and energy consumption for solvent regeneration also increase (Normann et al., 2019; Sundqvist et al., 2018). Fully electrified ironmaking would be a transformative innovation breakthrough: research and development has been intensifying for both molten oxide electrolysis (MOE, operating at 1600 °C) and electrowinning (operating at around 100 °C) (Cavaliere, 2019). Nonetheless, this technology is in its infancy, with commercialisation not expected before 2035 (MPP, 2022).

Currently, the most promising path forward is H_2-based DRI production, a modification to the existing natural gas-based process, which is rapidly approaching commercialisation. Although DRI reactors have not yet surfaced in Ukraine, the DRI route accounted for 8% of global iron output in 2021 (World Steel, 2022). Swedish companies HYBRIT and H2GS, amongst others, are in the race for the world's first commercial 100% green H_2-based DRI plant - the former successfully completed a pilot-scale H_2-DRI plant in 2020, and underground H_2 storage in 2022 (SSAB, 2022), and the latter is working towards a commercial-scale plant by 2025 (H2 Green Steel, 2022). The Ukrainian government already sees a push for a green H_2-based steel supply chain as a part of the country's recovery strategy (NRC, 2022). Hence, green H_2-based steelmaking is poised as the technology that will transform the steel sector and is spotlighted in this study for producing both green steel and green HBI.

In this work, the phase-out of current fossil-based steelmaking alongside the phase-in of low and near-zero emissions steelmaking was explored. Two main transitional technologies were investigated: firstly, the DRI-EAF route, using various natural gas (NG) and hydrogen (H_2) blends as the reducing gas. Natural gas-based DRI is a mature technology that supports up to 30% H_2 substitution in the feed gas, without any infrastructure changes (Astoria et al., 2022), whilst infrastructure upgrades can support H_2 substitution up to 100% (Vogl et al., 2018). Secondly, since DR shaft furnaces do not support BF-grade iron ore, and iron ore supply quality is constrained (Kim and Sohn, 2022), the DRI-melter-BOF route was explored, with an Open Slag Bath Furnace (OSBF) as the melting unit. Enterprisingly, this route provides a production avenue for lower quality ores and takes advantage of existing

BOF assets. The production and trade of HBI as an agent for iron and steelmaking dislocation was also investigated. Regarding energy sources, the Ukrainian sector may build on existing energy infrastructure, which is nuclear dependent, with rising solar and wind capacity. Pre-war (in 2021), the nation produced 155 terawatt-hours (TWh), 55% from nuclear, 24% coal, 7% hydro, 7% gas, 4% solar, 3% wind, and 1% geothermal/biomass (BP, 2022). Hence, in addition to CO_2-free nuclear and hydropower resources, this study investigates the upscaling of *onshore* hybrid solar and wind plants, and *offshore* wind plants.

High-quality renewable energy, that produces cheap CO_2-free electricity and hydrogen, underpins the business case for green H_2-based steel production (Devlin et al., 2023). Green H_2 is produced via electrolysis - the splitting of water (H_2O) molecules into its constituent elements - using renewable electricity. H_2 facilitates iron ore reduction, providing the chemical energy input that replaces coal. Because of its low density, the transport of gaseous hydrogen is very expensive in the absence of a pipeline. In order to ameliorate the transport costs, many projects consider the use of hydrogen derivatives, which are denser than hydrogen and can, therefore, be transported and stored more cheaply. There are several derivatives under contention: liquified hydrogen, green methanol, synthetic green natural gas, and green ammonia are all discussed in the literature as potential choices. No clear consensus has formed in the literature so far regarding the best hydrogen carrier. Here, we focus on green ammonia (NH_3) as a potential derivative, as it has several advantages: it is liquid under comparatively mild conditions; it can be produced from only water, power and air, and does not need access to a source of carbon; and it is already synthesised and transported globally in very large volumes. Upon delivery to a steel plant, it can be cracked back into the hydrogen that is required for a DRI (Salmon and Bañares-Alcántara, 2021). To secure the immense quantity of zero emissions electricity and hydrogen required for green steel supply chains, green NH_3 may become a critical supply chain mobiliser.

2.2. Techno-economic assessments of green H_2-based steel production

This study augments the growing repository of decarbonisation literature covering techno-economic locational assessments for green H_2-based steel production, of which the key contributions are detailed in Table 1. Most studies have explored ideal locations and/or supply chain configurations, given local resource and/or green commodity import availability. Whilst some investigated grid-powered production, others modelled islanded energy systems. Thus far, the geographical focus has been Europe. Existing literature on decarbonising the Ukrainian steel sector is scarce: whilst a broad vision for the sustainable future of Ukraine's steel industry was provided (Shatokha, 2016), the only technology focus was on utilising best available technologies in existing BF routes (Shatokha et al., 2020).

2.3. Research gaps

Multiple research gaps can be identified from the summary of current literature. Firstly, the lack of geographical coverage of developing (low- and middle-income) nations or unstable socio-political contexts. Secondly, whilst plant-level optimisation and supply chain simulation has been explored, supply chain optimisation has not. According to the authors' knowledge, supply chain optimisation is absent in steel decarbonisation literature, where the movement of energy and raw materials to iron and steelmaking production sites, and then onwards to demand markets, is assessed. This study fills the literature gaps by adopting a geospatial explicit optimisation modelling approach and selecting post-war Ukraine as the case study - a nation with substantial iron ore resources and steelmaking capabilities, as well as an urgency for industrial growth given its shattered economy, high unemployment, and destroyed iron and steel assets. This work builds on the authors' previous studies (Devlin et al., 2023; Devlin and Yang, 2022) in three major aspects: (i) expanding the spatial scope to national-level with regional

Table 1

Summary of key literature focused on techno-economic assessments of green H_2-based steel production. The levelised cost of steel (LCOS) production is used as a key economic measure (presented below in equivalent USD).

Source	Location(s)	Method	Findings
Bhaskar et al. (2022)	Norway	Optimisation model of H_2-DRI-EAF production with H_2 and HBI storage, and time-variable electricity prices.	Norway is ideally located near raw material inputs and European green markets, with LCOS estimated at $622–722/t steel. Procuring electricity from day-ahead markets, compared to a fixed power price, could reduce the LCOS by 15%.
Devlin and Yang (2022)	Australia and Japan	Scenario-based simulation model which varied in supply chain configuration and H_2 energy carrier (LH_2, NH_3) and forecast to 2030 and 2050.	Co-locating production processes with material and energy inputs will reduce energy consumption by 31% and LCOS by 24% (average from 2030 to 2050 results), when compared to exporting H_2 and iron ore to intercontinental steel producers. Australia is ideally placed for green iron and/or steel production.
Devlin et al. (2023)	Global	Optimisation model of H_2-DRI-EAF production using variable wind and/or solar power, forecast to 2030, 2040, and 2050, with each case repeated 5 times for various historical RE capacity factors (2015–2019).	Low-cost green H_2-based steel was located nearby the tropic of Capricorn and Cancer, characterised by superior solar with supplementary onshore wind. By 2050, the most favourable locations had a LCOS of $535/t and, if coking coal prices remain high, renewables-based steel could attain market competitiveness from 2030.
Lopez et al. (2023)	Germany, Spain, and Finland	Scenario-based simulation model which varied in supply chain configuration and forecast to 2020, 2030, 2040, and 2050.	HBI imports (via ship) are more cost-effective than H_2 imports (via pipeline) from Morocco. Steel production using HBI imports from Morocco is competitive with local European supply chains. Lowest H_2-DRI-EAF costs were in solar-rich Spain with LCOS decreasing from $512/t steel in 2030 to $386/t steel in 2050. Especially large potential in Australia and Brazil for green steel production exists due to copious ore resources.
Otto et al. (2017)	Germany	Scenario-based simulation model which varied in technology dependence.	Nation-wide, integration of 237 TWh of renewable electrical power would be required to switch to green H_2-based steelmaking, with emissions reducing to 5% of 1990 levels.
Pimm et al. (2021)	UK	Optimisation model of H_2-DRI-EAF production using variable wind and/or solar power based on	The optimal energy system comprises (oversized) electrolysers, solar and wind energy, combined cycle gas with

(*continued on next page*)

Table 1 (*continued*)

Source	Location(s)	Method	Findings
		historical RE capacity factors (2000–2019 data used, aggregated to four time-slices per month).	carbon capture, H_2 storage, and compressed air energy storage. A portion (e.g. 20%) of dispatchable power allowance is influential in reducing H_2 storage requirements. Before 2030, the costs of switching to H_2-based steelmaking could be less than carbon price forecasts.
Toktarova et al. (2022)	Northern Europe	Scenario-based optimisation model which varied in economic parameters, DR furnace flexibility, and steel demand location.	Low-cost electricity is the primary cost driver for location selection of electrified steel plants and may vary from present day sites. Solar and wind capacity growth will best meet increased electricity demand (whilst gas base load reduces).
Trollip et al. (2022)	South Africa	Scenario-based optimisation model for green H_2-based DRI production, using solar resources in South Africa and EU electricity market prices.	South Africa could produce green HBI at \$395/t HBI. For steelmaking in the EU to be competitive with HBI imports from South Africa, electricity prices must fall below \$38/MWh.
Wang et al. (2023)	Australia	Geospatial resource mapping assessment followed by an optimisation model of H_2-DRI-EAF production using variable wind and/or solar power (under fixed ratios of 100% solar/wind, or 50% each).	Correlation exists between the location of iron ore deposits and high-quality renewables, as in the Pilbara region of Western Australia and Eyre Peninsula of South Australia. Additionally, new steelmaking activities could benefit from existing power and transport infrastructure from mining operations. LCOS estimated at \$500/t steel in 2050.

export links, (ii) incorporating existing asset inertia, and a range of transitory technology and fuel options, and (iii) moving beyond pure techno-economics of industrial location theory by framing the analysis around geopolitical considerations and climate policies. The approach taken enabled a rigorous evaluation of steel supply chain networks on the pathway to near-zero emissions by 2050.

3. Methods

3.1. Optimising the steel sector's transition to near zero emissions

The supply chain optimisation model utilises spatially granular data to determine where, when, and what iron and steelmaking technology investment should occur, as depicted in Fig. 1. The model was developed using GAMS (General Algebraic Modelling System) software as a Mixed Integer Linear Programming (MILP) problem. It optimised for lowest net present value (NPV) over the 20-year project lifetime, with a discount rate of 8% using the CPLEX solver. The movement of materials and energy were informed by natural resource constraints (e.g., land availability for installation of RE infrastructure, iron ore reserves, and metallurgical coal reserves), circularity constraints (scrap steel availability), steel demand profiles (domestic and exports), and carbon pricing mechanisms. Possible supply chain nodes included manufacturing sites, ports, rail border crossings, ore mines, metallurgical coal mines, natural gas fields, offshore wind sites, nuclear power plants, and hydropower pants. Importantly, both brownfield and greenfield sites were explored over the entire nation. Refer to Supplementary Information (SI) Section S2.3 for detailed model description and equations.

In Ukraine, as defined by the pre-2014 national boundaries, 73 possible iron and steel plant locations, and over 100 possible renewable energy production locations were considered at 1° × 1° grid spatial resolution (about 111 km (latitude) x 73 km (longitude)). Electricity generation is decentralised - each grid can produce its own renewable power or import electricity/H_2/NH_3 from other grids. Green commodities (electricity, H_2 and NH_3) can be sourced from onshore hybrid solar/wind, offshore wind, nuclear or hydropower plants. This study builds on modelling competencies within previous work (Devlin et al., 2023) for 100% green H_2-DRI-EAF steel production at the facility-level, with important extensions regarding energy source and technology diversification, supply chain integration, carbon policy economics, and existing asset incorporation. The model was repeated in 2030, 2040, and 2050 with physical asset inertia (i.e., carry-over of installed capacities) and cumulative natural resource consumption (affecting land availability, ore reserves, and metallurgical coal reserves). This modelling approach allowed exploration of the interplay between operational costs, capital costs, debt incurred for early furnace retirement, and carbon prices. The inherent uncertainty involved in future energy system modelling, especially in this unstable socio-political context, has been reduced by using detailed local resource and economic input data (as specified in Table 2).

The major carbon pricing mechanism affecting Ukraine is the EU-ETS, a 'cap and trade' market-based mechanism, and its complementary Carbon Border Adjustment Mechanism (CBAM), which imposes a price on carbon within goods imported to the EU. Under anticipated EU accession, all Ukrainian steel production will be subject to the EU-ETS, and on the pathway to EU accession, a similar, yet more moderate, Ukrainian carbon pricing mechanism is likely to be in place (the UA-ETS, see Table 3), with exports subject to the EU CBAM.

3.2. Optimising renewables-based electricity, hydrogen, and ammonia production

This study utilised an integrated energy-production system to optimise the production of three separate renewable-energy derived products: electricity, hydrogen, and ammonia (shown in SI Figure S2.1). In each case, the model considered both the local renewable energy profile and the capital cost of each piece of equipment to determine the system design that minimised the NPV, whilst satisfying the product demand. The MILP optimisation was implemented in Python, using the PyPSA module and Gurobi solver. This model was repeated for each product with the requirement of firm power/H_2/NH_3, i.e., continuous supply, which could feed the continuous production demands of the steel industry. Green electron production from the solar panels/wind turbines were either directly utilised, stored (in lithium-ion batteries, in compressed gaseous H_2 tanks, or liquefied NH_3 tanks), or curtailed in every hour over the 8760 h in the modelled year.

Having determined the minimum cost of the system for energy production, the maximum capacity for energy production of the specific system in every location was then estimated for every 1° × 1° grid. Land/sea use reduction factors were applied in acknowledgement that (i) not all areas are suitable for RE infrastructure, nor (ii) can the entire RE potential of an area be solely dedicated to green steel production. These factors are described in Table 4 and utilised in the equations listed in SI Section S2.1.

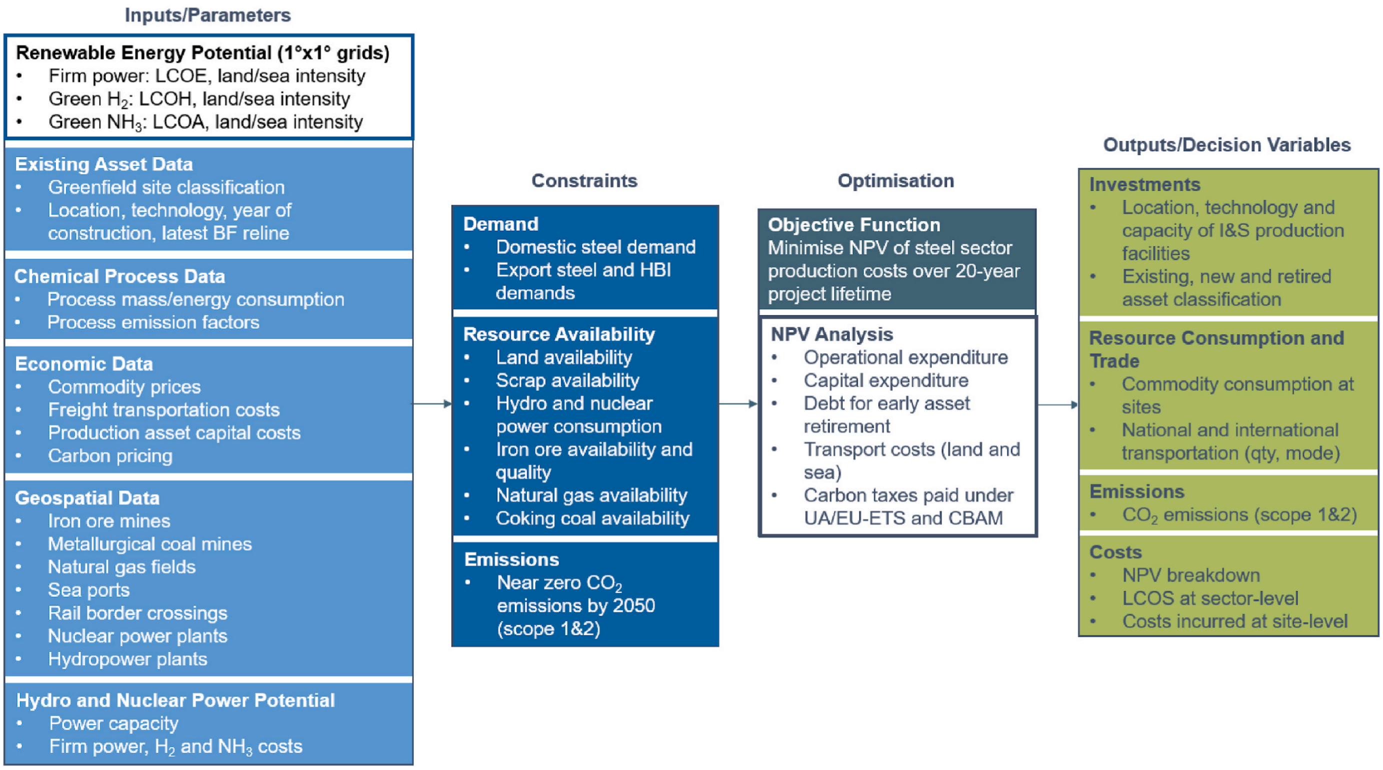

Fig. 1. Schematic of the green steel transition model. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.3. *Establishing scenarios and forecasting steel demand*

Two distinct scenarios were developed, which reflect the complexity of war and the uncertainty of post-war outcomes, as detailed in Table 5. Underlying both scenarios are the assumptions that Ukraine will become a member of the EU, with carbon pricing mechanisms enforced, and the armed conflict is resolved, thereby reducing investment risk, and creating the fundamental economic conditions for market-competitive green steel.

Dynamic material flow analysis (MFA) was utilised to understand the historical inflows, outflows, and in-use stocks of steel in Ukraine, facilitating projections of post-consumer steel demand and scrap supply out to 2050. Historical steel consumption allocation across the key product categories (transportation, machinery, construction, and appliances/packaging) were estimated using input-output (I–O) tables from the available data years: 1972 (U.S.B.C, 1982), 1990–1995 (Aptekar and Amosha, 2005), and 2013–2020 (Ukrstat, 1990-2021). Following work by Pauliuk et al. (2013), saturation levels for mature steel stocks were determined to be 13 ± 2 tonnes/capita, and a normally distributed lifetime assumed with standard deviation of 0.3 to the mean. Scrap steel availability was determined using a 90% recycling rate (World Steel, 2023) of post-consumer steel outflows. Refer to SI Section S2.2 for formulae and lifetime distribution data.

Domestic steel demand was calculated as the sum of population-based consumption and reconstruction-related needs. For population-based steel consumption, annual per capita consumption rates were multiplied by the projected population, as specified in Table 5 for each scenario. For reconstruction-related needs, direct damage to Ukraine's buildings and infrastructure in the first 12-months of the war has been estimated at $134.7 bn (WB, 2023), which will lead to a total demand boost of $12.63 bn per year for Ukraine's construction industry over a reconstruction period of 10 years. Refer to SI Table S1.12 and SI Section 2.4.3 for details. This will generate $2.77 bn of additional steel demand per year, equivalent to 15.5% of the 2021 annual output, or 3.32 Mtpa steel. It can be reasonably assumed that damage will increase at least two-fold in the subsequent hostilities from February 2023 onwards, totalling 66.4 Mt steel for post-war reconstruction needs over a period of 20 years. Post-war reconstruction will significantly boost demand for steel products, spanning infrastructure repair, defence requisites, and economic revival, and it is in Ukraine's economic interest to meet this surge in steel demand via domestic production.

Export demand for green HBI and green steel products were informed largely by historical trade patterns, and the landscape of existing steelmaking technologies within importing nations. Exports were distributed over the 13 EU member states and the UK. To safeguard supplier diversity, exports could not exceed 35% of any nation's projected demand (given by Bataille et al. (2021)), according to the current forecast of 2.2Bt of steel demand in 2050. HBI could be produced using BF-grade or DR-grade ore, and the demand of each sub-product was a function of the relative existing capacities of BF-BOF (supporting BF-grade HBI via the DRI-melt-BOF route) and EAF (supporting DR-grade HBI via the DRI-EAF route) plants in each importing country. The fundamental assumption was the maintenance of an export-oriented industry in Ukraine. Over the past decade, approximately 65% of the produced steel has been shipped overseas (refer to SI Table S.1.11); the steel sector has generated around 25% of the nation's commodity exports, with $16 bn worth of exports in 2021 alone (Ukrstat, 2008). Pre-invasion, Ukraine ranked 14th amongst steel-producing countries, with a total output of 21.4 Mt of crude steel, and 15.7 Mt exported (World Steel, 2021). To note, Ukrainian steel products have been historically subjected to a vast variety of anti-dumping measures by countless foreign trade partners (refer to SI Table S3.3). A green steel transition, thus, is vital for this sector to survive growing de-carbonisation pressures as well as trade barriers in the country's key export markets.

Table 2
Key data inputs to the supply chain optimisation model.

Data type	Description and source(s)
Existing iron and steelmaking assets	Ukraine's 19 BFs, 13 BOFs, 8 OHFs and 3 EAFs of either operating or mothballed status (GEM, 2023d) were modelled as existing assets, with the exclusion of Mariupol's Azovstal and Ilyich Iron and Steel Works, as they are at least partially destroyed, and the extent of damage and restoration requirements are unclear (WB, 2023). Asset ages and BF relining campaign lives (GEM, 2023a) were used to determine asset depreciation.
RE-based electricity, H_2, and NH_3 production costs and land/sea intensities	The levelised cost of electricity (LCOE), hydrogen (LCOH) and ammonia (LCOA) are outputs from a separate RE optimisation model, which produces green commodities for continuous supply to industrial users. Sea and/or land consumption rates are also determined (refer to Section 3.2).
Nuclear/hydropower-based electricity, H_2, and NH_3 production costs	The base price of nuclear/hydropower was assumed to be $20/MWh based on the historical range in recent years: $18–22/MWh for hydropower (NERC, 2018) and $18–29/MWh for nuclear power (Accounting Chamber of Ukraine, 2020). Production costs of H_2 using continuous electricity supply were determined using a simplified levelised cost calculation based on low temperature electrolysers (refer to SI Table S2.3 for unit costs). Consequently, NH_3 costs were determined by adding on energy demand and costs for the Haber-Bosch process (refer to SI Table S2.5 for unit costs).
Nuclear and hydro power capacities	For nuclear capacity, only two nuclear reactors of Ukraine's current fleet of 15 (GEM, 2023c) will still be operational past 2050, based on an expected lifetime of 60 years for newer units (World Nuclear Association, 2022). The model assumes that these two reactors are upgraded to 150% of current capacity, totalling 3000 MW (22% of current capacity), which continue to operate at a capacity factor of 71% (based on 86 TWh of nuclear power produced in 2021 (BP, 2022)). For hydropower capacity, the ten operational plants sum to a combined capacity of 6247 MW (excluding the destroyed Kakhovka Dam and Hydroelectric Power Plant) (GEM, 2023b). The model assumes a capacity factor of 30% across the existing HPP asset fleet, and that the steel sector can consume 20% of the produced electricity.
Geospatial data	In addition to the grid-level RE potential data and coordinate-level GEM data for steelmaking assets, nuclear power plants, and hydropower plants, geospatial data were integrated for natural gas fields (EITI, 2020), iron ore mines (GMK, 2023), metallurgical coal mines (Amosha et al., 2017), and sea ports (Shipnext, 2023).
Commodity prices	The most critical energy and material inputs for steelmaking are commodities traded on global spot markets, hence, prices fluctuate significantly over time. Due to the high number of variables already considered in the model, constant prices were assumed, based on historical averages: DR-grade iron ore was priced at $100/t (Black Iron, 2023), BF-grade iron ore at $80/t (WB, 2022), scrap at $300/t (GMK, 2021), natural gas at $25/MWh (Eurostat, 2023), and metallurgical coal at $200/t (DISR, 2023). For the complete list of commodity prices, refer to SI Table S2.13. A sensitivity analysis on these economic inputs was conducted, as shown in the SI Tables S1.1-S1.4.
Freight transportation costs: railway freight (dry bulk goods), pipeline (liquefied NH_3, NG) and power grids (electricity)	The unit cost of dry bulk railway freight was $0.025/t/km (Forbes UA, 2022), with 30% fuel consumption reduction considered on the return leg. Pipeline costs for liquefied NH_3 were $0.05/t/km (Nayak-Luke et al., 2021) and for NG $0.08/t/km (DeSantis et al., 2021). The electricity transmission tariff for green metallurgical enterprises of $5.67/MWh/km was used, as set by the Ukrainian National Commission for State Regulation of Energy and Public Utilities (NERC, 2022). For related equations refer to SI Section S2.3.10.
Chemical process data	For selected iron and steel production processes (as listed in SI Section S2.3.2) as well as NH_3 cracking (needed to transform NH_3 back to H_2 for use in the DR shaft furnace) data were collected from various sources, as detailed in SI Table S2.11.
Production asset capital costs	Iron and steelmaking furnace capital costs, and the NH_3 cracker unit cost, have been collected from various sources as detailed in SI Table S2.14.
Emissions boundary and emission factors	Emissions were determined as the sum of scope 1 and 2 emissions (although since all electricity was CO_2-free, scope 2 emissions were nil). Upstream scope 3 emissions from raw material extraction, preparation, and transportation were excluded. The emissions boundary was drawn around sites, up to the point of crude steel production. For scope 1 emission factors, refer to SI Table S2.11, and for related equations, refer to SI Section S2.3.9.

3.4. Deriving economic multipliers from input-output analysis

I–O analysis utilises a systems approach to the economy, stressing inter-industrial or sectoral interdependence, whereby the output of one sector is often the input of another (Leontief, 1966). This study employs macro-economic I-O analysis to (i) examine the impact of the Ukrainian steel industry on production, income, and growth, and (ii) model the long-term effects of post-war reconstruction on domestic steel demand, and on the wider economy. Through a detailed disaggregation of economic activities, Leontief inverse matrices were developed, providing quantitative transaction relationships between industrial components of a given economic system (Leontief, 2008). I–O multiplier analysis was selected as the most analytically rigorous approach to regional modelling, in comparison with the two alternatives – the Keynesian income multiplier and economic base models (McCann, 2013). Three core assumptions were applied: proportionality (i.e., demand for intermediate inputs is a linear function of output), constant returns, and no substitution between different inputs or factors of production (Munroe and Biles, 2005). Following guidance from key practitioners (Eurostat, 2008; ONS, 2022), and based on the 1990-2021 data from the Ukraine State Statistics Service, an economic I-O analysis of the historical coal-based steel sector was conducted for 2014 and 2021. In addition, the macroeconomic impact of the optimised future green steel sector was modelled for national output, income, and gross value added (GVA) patterns. For comparison, the economic impact of the same magnitude of steel

Table 3

Forecast EU-ETS and UA-ETS policy features. Emission-intensity benchmarks from 2021 to 2025 are based on the top-10% most efficient facilities with an annual linear benchmark reduction factor of 4.5% from 2026 to 4.6% from 2029. Free allowances reach zero by 2035. Steel classes were slightly modified, adopting 'primary' and 'secondary' as extensions of the actual 'hot metal' and 'EAF carbon steel' classifications, respectively.

		Unit	2025	2030	2040	2050	Source
EU-ETS and CBAM	Emission-intensity threshold (primary steel)	t CO_2/t steel (scope 1&2)	1.288	1.021	0.638	0.398	European Parliament Research Service (Erbach and Foukalová, 2023); Eurofer (2021)
	Emission-intensity threshold (secondary steel)	t CO_2/t steel (scope 1&2)	0.215	0.170	0.106	0.066	
	Reduction factor for free allowances	–	100%	50%	0%	0%	
	Carbon price	USD/t CO_2	70	100	200	250	OECD (2021); IEA (2022)
UA-ETS	Reduction factor for free allowances	–	–	75%	0%	0%	Kyiv School of Economics, medium scenario (KSE, 2021)
	Carbon price	USD/t CO_2	–	75	150	188	

production under traditional coal-based steel scenarios was assessed and I-O modelled using the latest pre-war output multipliers. Refer to SI Section S2.4 for further details.

4. Results and discussion

4.1. *Green iron and steel growth is underpinned by strong regional demand and product market competitiveness*

Trade links with regions governed by strong climate policies drive progress in decarbonising export-oriented steel sectors. Post-war reconstruction efforts will initially drive steel demand, but will be insufficient alone to propel sustainable industry growth. In the *Strong Recovery* scenario, EU accession is achieved by 2030, resulting in immediate realisation of 'demand-pull' for green steel and HBI products from export markets; the steel export ratio is estimated to be 58% in 2030, expanding to 77% by 2050 (on par with the pre-war ratio, as shown in Fig. 2). It is essential to take advantage of two important export markets: green steel, and green HBI. Whilst green steel offers greater export revenue prospects, HBI will be an extremely valuable negotiation tool for trade partnerships. Unlike the traditional integrated BF-BOF production route, ironmaking and steelmaking can be separated in the DRI-EAF route through the transportation of HBI. Traditional large EU steel manufacturing economies, e.g., Germany and Spain, will be more open to benefit-sharing agreements, whereby Ukraine carries out ironmaking, whilst they maintain steelmaking capacity and value-adding downstream processes. This approach safeguards jobs for both parties, whilst improving overall market competitiveness. Ukraine would still obtain significant export revenues from green HBI: if the EAF is charged with 100% DRI, HBI costs would represent about 75% of the cost of steel. The maximum total export quantity for any scenario is 17 Mtpa of steel equivalents, representing a reasonable 11% of the total demand from EU-27 and the UK in 2050. Moreover, long-term trade partnerships with numerous countries and modest export expansion plans support investment risk reduction and green steel sectoral growth.

Market competitiveness is necessary to establish and sustain new trade partnerships. In the context of EU accession, Ukraine's steel and HBI exports will shift away from traditional North African and Middle Eastern markets, and towards EU and UK markets (as shown in SI Figures S1.7-S1.9). Although pre-war Ukraine exported 15 Mtpa steel products, only 2.5 Mtpa was directed towards European nations (Eurofer, 2022). Post-war exports are anticipated to be directed to EU and UK neighbours, as they have clear carbon policies, including border adjustment mechanisms. To secure a reasonable share of Europe's green steel market, a required levelised cost of steel (LCOS) less than or equal to $500–586/t has been estimated (Lopez et al., 2022). Favourably, Ukraine's green LCOS range in ideal locations has been calculated in this study to be $440–600/t. At the lower end, H_2-DRI-EAF production is powered by firm electricity from hydro or nuclear power, where costs are minimised due to the fully depreciated assets of these mature energy projects (although for new builds, these energy resources may prove very expensive). At the pricier end, co-located H_2-DRI-EAF production will cost around $587/t steel, based on cost-competitive continuous supply of electricity ($64/MWh) and green hydrogen ($3.31/kg H_2), using new-build onshore hybrid solar and wind power (see Fig. 3). About 75% of the costs of steelmaking occur up to the point of iron production; the levelised cost of green HBI is estimated at $440/t, and with cheaper firm electricity of $20/MWh, costs will reduce to $290/t. This is competitive with green HBI costs estimated for other ore-producing regions, e.g., $395/t in South Africa (Trollip et al., 2022), especially considering the reduced transportation costs. Tapping into high quality renewables is essential for HBI and steel cost reduction, and export market retention.

4.2. *Multiple zero emissions energy sources support the transition*

Significant temporal and spatial variability in renewable potential exists across the region. The LCOE for firm power from onshore hybrid solar and wind energy is quite high, varying from $86–161/MWh in 2030, $70–117/MWh in 2040, and $58–91/MWh in 2050 (as shown in Fig. 3a). Despite the strength of wind resources in Ukraine (in 2019, the average hourly power capacity for wind was 0.32 and for solar 0.14), the high expense of wind turbines in comparison to solar panels favours the latter. Solar capacity as a portion of total renewable energy capacity is estimated to average 68% in 2030, increasing to 78% in 2050. Daily and seasonal troughs in solar power are somewhat balanced by peaks in wind power, with reduced intermittency and increased wind speeds observed in winter months, when solar power is reduced. The LCOH is similarly un-exceptional: results vary from $3.96–13.76/kg H_2 in 2030, $3.19–9.45/kg H_2 in 2040, and $2.65–6.91/kg H_2 in 2050 (as shown in Fig. 3b), which for even the best locations is above the EU's goal of electrolytic hydrogen costs being below $2.2/kg H_2 (€2/kg) (EurActiv, 2021). The LCOA varies from $450–1300/t NH_3 in 2030, $389–1027/t NH_3 in 2040, and $346–829/t NH_3 in 2050 (as shown in Fig. 3c), with the upper quartile in 2040 and 2050 being competitive with the conventional emissions-intensive natural gas-based production method of $300–550/t NH_3 (IEA, 2020). Ideal geographical locations for onshore green power and fuel production lie in far southern, eastern, northern and north-western areas of Ukraine, which strike a balance between reliability (i.e., minimal intermittency) and intensity (i.e., power output) of solar and wind resources.

Utilising hydropower and nuclear power can reduce energy costs, but capacity is highly constrained. For firm electricity delivered at $20/MWh, the LCOH is outstandingly viable at $1.23, $1.14, and $1.06/kg H_2 in 2030, 2040 and 2050, respectively. This cost-competitiveness is extended to ammonia, costing $321, $305, and $291/t NH_3 in 2030, 2040, and 2050, respectively. However, under HPP constraints, the steel sector may consume 19 TWh of electricity annually, which can only power 5 Mtpa of green H_2-DRI-EAF steel production, whilst under NPP constraints, the maximum consumption is 3.2 TWh annually, or 1 Mtpa

Table 4
Key data inputs to the RE optimisation model.

Data type	Description and source(s)
Solar and wind power potential	Weather data were obtained for the year 2019 from the ERA5 dataset (Hersbach et al., 2023) and converted into renewable energy profiles using a standard wind turbine curve (considering turbines at 100m altitudes and the Vestas 3 MW model) and the python library PVLib (using the general Sandia National Labs design for a panel (Holmgren et al., 2018)).
Unit costs for renewable electricity, hydrogen, and ammonia production, and storage	To forecast unit costs of emerging renewable electricity and electrolyser technology to 2050, current costs for wind and solar projects in Ukraine were sought (refer to SI Table S2.2) and learning curves from the Oxford Institute of New Economic Thinking applied (Way et al., 2022). Since Ukraine has no existing offshore wind projects, global average floating and fixed capital costs were utilised (Salmon and Bañares-Alcántara, 2022). In oceans, at water depths of less than 50m, fixed-bottom wind turbines can be installed; for greater depths, up to 1000m, more expensive floating turbines were required; for depths over 1000m, no wind turbines installations were considered. Hydrogen production is based on water electrolysis using low-temperature electrolysers. For the full list of time-variable cost parameters, refer to SI Table S2.3 and Table S2.5. Relatedly, for electrolyser and fuel cell efficiencies, refer to SI Table S2.4.
Land type classification	MODIS5 land classification data (Friedl and Sulla-Menashe, 2019), which use satellite imagery to determine the current use of the land, of which there are 17 possible land use classifications.
Maximum land consumption for RE infrastructure as fraction of total land availability	For each classification, estimates from literature (Salmon and Bañares-Alcántara, 2022) were applied, which determined the maximum fraction of land that could plausibly be used for renewable energy production. Land was also excluded if it was designated as protected by the UN (Protected ProtectedPlanet, 2023), or if the local slope was greater than 15°. Refer to SI Table S2.1.
Maximum sea consumption for RE infrastructure as fraction of sea availability	For the Black Sea and Azov Sea, an assumption of 50% of the grid area within Ukraine's marine exclusive economic zone was made, considering high-density marine traffic, and marine protected areas (Begun et al., 2012).
Maximum steel sector fraction of maximum RE infrastructure consumption	An assumption of 20% was made for the steel sector's portioned consumption of land, given that pre-war, the Ukrainian steel sector consumed around 20% of final energy consumption. This calculation was based on national consumption of 2.156 million TJ (IEA, 2021), and energy consumption rates of 23.0 GJ/t consumed by the BF-BOF/OHF route (Metinvest, 2020), and 9.4 GJ/t consumed by the EAF route (Interpipe, 2021).

of green H_2-DRI-EAF steel only. In addition, whilst solar and wind projects offer rapid project development and construction times (e.g., a recent 240 MW solar farm in Ukraine took just 8 months to build (DTEK, 2019), and a 114 MW wind farm took 1.5 years, even during the war (DTEK, 2023)), nuclear projects require decades from final investment decision to operation, with the construction period alone lasting about 9 years (World Nuclear Association, 2020). Hence, whilst Ukraine's mature CO_2-free energy infrastructure has a role to play, energy system expansion has to rely on solar and wind.

Table 5
Scenario definition.

Parameter	Strong Recovery	Slow Recovery
Land occupation	Full territorial liberation, including the Donbas and Crimea.	Partial liberation of territories; land currently occupied by Russian forces remains under Russian control.
Domestic demand	Strong domestic demand driven by 90% of refugees returning to Ukraine post-war (see Kulu et al. (2023)) and complete post-war reconstruction over a 20-year period. Domestic steel consumption rates reach 165 kg/capita by 2050 (from 60 kg/capita during the war).	Weak domestic demand driven by 10% of refugees returning to Ukraine post-war (see Kulu et al. (2023)) and partial (80%) post-war reconstruction over a 20-year period. Domestic steel consumption rates reach 150 kg/capita by 2050 (from 60 kg/capita during the war).
Exports	Strong EU export market for green steel and green HBI, given EU membership, and CBAM imposed on extra-regional competitors. Exports reach 16 Mtpa steel equivalents by 2050.	Reasonable EU export market for green steel and green HBI, given eventual EU membership, and CBAM imposed on extra-regional competitors. Exports reach 11 Mtpa steel equivalents by 2050.
Trade routes	All sea routes open and rail de-bottlenecked.	No access to Azov Sea ports, but rail de-bottlenecked.
EU accession	Rapid EU accession (by 2030).	Slow EU accession (by 2040).
Carbon policies	EU-ETS adopted.	Medium UA-ETS implemented in 2030, and CBAM is imposed on EU/UK exports. EU-ETS adopted by 2040.
DR-grade ore availability	DR-grade ore supply expands (in response to research & development (R&D), and investment in beneficiation and pelletisation capacity), reaching 23.7 Mtpa in 2050 (34% of total ore products, satisfying 80% of total production demand).	Stagnated DR-grade ore supply (with minimal R&D and investment in beneficiation and pelletisation capacity), reaching 11.9 Mtpa in 2050 (17% of total ore products, satisfying 64% of total production demand).

Renewable energy potential is high and aligns well with literature. Nation-wide, the onshore solar and wind power potential in 2030 sums up to 2182 TWh (with a maximum of 436 TWh allocated to the steel sector), calculated with hourly wind speed at over 100 locations. To note, this study's estimate is 70% greater than the earlier figures produced by the Ukrainian Institute of Renewable Energy (Kudria, 2020). At the same time, the estimated green H_2 potential of 40.8 Mtpa (with a maximum of 8.3 Mtpa allocated to the steel sector) aligns closely with the Institute's wind-to-H_2 assessment (Kudria et al., 2021). The combined sea capacity for energy production stands at 205 GW, producing 288 TWh in 2050, equivalent to 54% of combined land capacity, and roughly aligning with World Bank estimate of 250 GW (WB, 2020). In this study, it is estimated that Ukraine comprises 12.7% of EU land which is available and suitable for installation of renewable energy infrastructure, preceded only by Spain (14.8%) and France (13.2%). Thus, Ukraine could be a significant contributor to EU energy security through production and export of energy-intensive manufactured products.

4.3. The sectoral transition is supported by well-timed investment, geographical and energy source diversity, and carbon pricing

A gradual, integrated sectoral plan to achieve near-zero emissions in 2050 supports a successful transition, with 2030 serving as a critical near-term milestone. Ukraine's existing coal-based steel plants are of significant capacity; nevertheless, Soviet-era assets are aged and carry little inertia, making green steel project investment more convincing. By 2030, 43 individual furnaces of operating/mothballed status will

Fig. 2. Ukraine steel demand projections, inclusive of exports, domestic consumption, and additional reconstruction needs, for the (a) *Strong Recovery* scenario, and (b) *Slow Recovery* scenario, respectively. Exports are a combination of green HBI and green steel, expressed as steel equivalents (given 0.9t HBI/t steel for 14% scrap charging during steelmaking). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

require an investment decision to continue/restart operations or towards entire retirement (comprising19 x BF, 13 x BOF, 8 x OHF, and 3 x EAF**)**. In 2030, the average BF age will be 61 years, and the average economic lifetime remaining on the latest reline will be 6 years (GEM, 2023a); therefore, few assets will face substantial debt for early retirement. In addition to the forthcoming carbon taxation of steel imports into the EU, UK, and other G7 nations, the age of BF assets in Ukraine, significantly greater than the global average of 25 years (Swalec and Grigsby-Schulte, 2023), supports the green investment case. In the *Strong Recovery* scenario, in 2030, just 12% of existing blast furnace capacity continues operation, totalling 3.5 Mtpa iron capacity across three plants. About one-third of basic oxygen furnaces continue to be used to facilitate integrated BF-BOF production, totalling 5.1 Mtpa. To meet the production gap, 10.8 Mtpa of additional DRI capacity, and 7.2 Mtpa of additional EAF capacity (on top of the existing 3.8 Mtpa of existing EAF capacity) will need to be installed. By 2050 (as shown in Fig. 4), across five brownfield (i.e., previous steelmaking site) and seven greenfield (i.e., new steelmaking site) locations, ironmaking capacity will be completely H_2-based, with steelmaking being distributed across the following processes: 42% scrap-based EAF, 37% DRI-charged EAF, and 22% melter-BOF. With less than three decades remaining to 2050, early investment in low and near-zero emissions production technology is vital to support a smooth clean energy transition.

Greenfield sites offer new opportunities to take advantage of high-quality renewables. The utility of green NH_3 and green HBI trade increases the geographical diversity of plant locations. Kryvyi Rih remains a dominant steelmaking city-region, adjacent to the nation's largest iron ore basin, and near Black Sea ports, with cheaper NH_3 transported from northern locations. In the balance of optimality and feasibility, iron and steel plants are concentrated in central-eastern and north-western regions. The need for greenfield projects in the western and central parts of the country will be especially high for Ukraine, if Russian-occupied territories, and the existing steel plants contained there, remain inaccessible (as shown in Fig. 5). In the *Slow Recovery* scenario, despite reduced steel demand, the lack of access to existing assets will drive new furnace investment. In 2030, 6.9 Mtpa of DRI and 4.9 Mtpa of EAF capacity would need to be installed across six greenfield sites and one brownfield. In 2040, further investment will total 2.1 Mtpa of DRI, 1.7 Mtpa of OSBF, and 2.2 Mtpa of EAF capacity. By 2050, any remaining BF capacity will be retired, with the production gap met by new DRI and melters (OSBFs), to be combined with existing BOF capacity for steelmaking with lower quality HBI. Greenfield construction in north-western regions - furthermost from the frontlines - could be prioritised, where new plants will benefit from cheap local renewables and proximity to rail border crossings.

The green steel transition is supported by mature CO_2-free energy sources (nuclear and hydropower), rather than natural gas. Although considered a transition fuel, natural gas is nonetheless a CO_2-producing fossil fuel, with carbon prices to be imposed on it. By 2050, domestic natural gas reserves will also likely be depleted, so it is logical for the

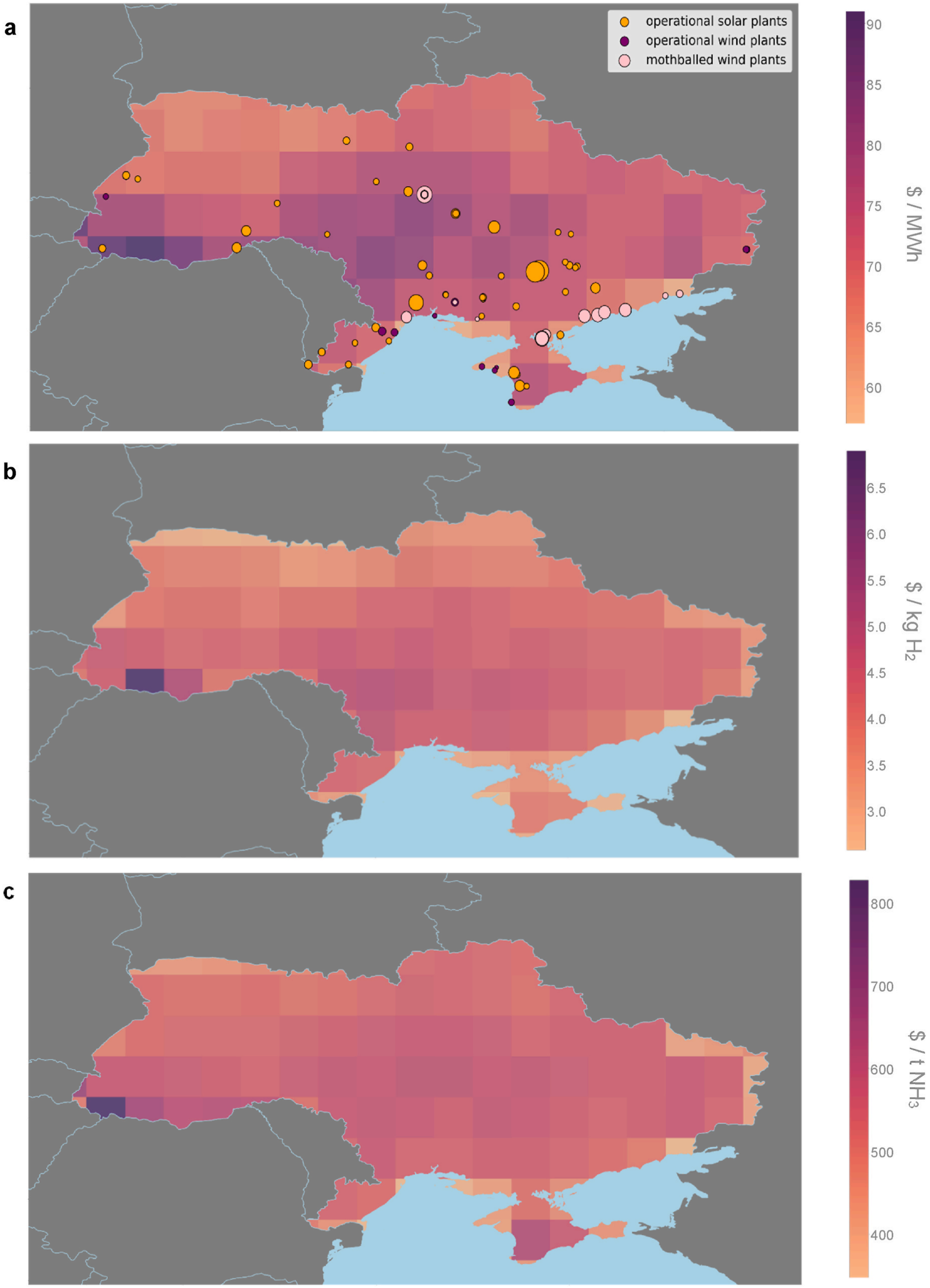

Fig. 3. Cost-minimised results of onshore hybrid solar and wind plant energy products installed in 2050: (a) Levelised cost of firm electricity (in USD/MWh), plotted with existing solar and wind installations (markers sized according to capacity); (b) Levelised cost of continually supplied hydrogen (in USD/t H_2); (c) Levelised cost of continually supplied ammonia (in USD/t NH_3).

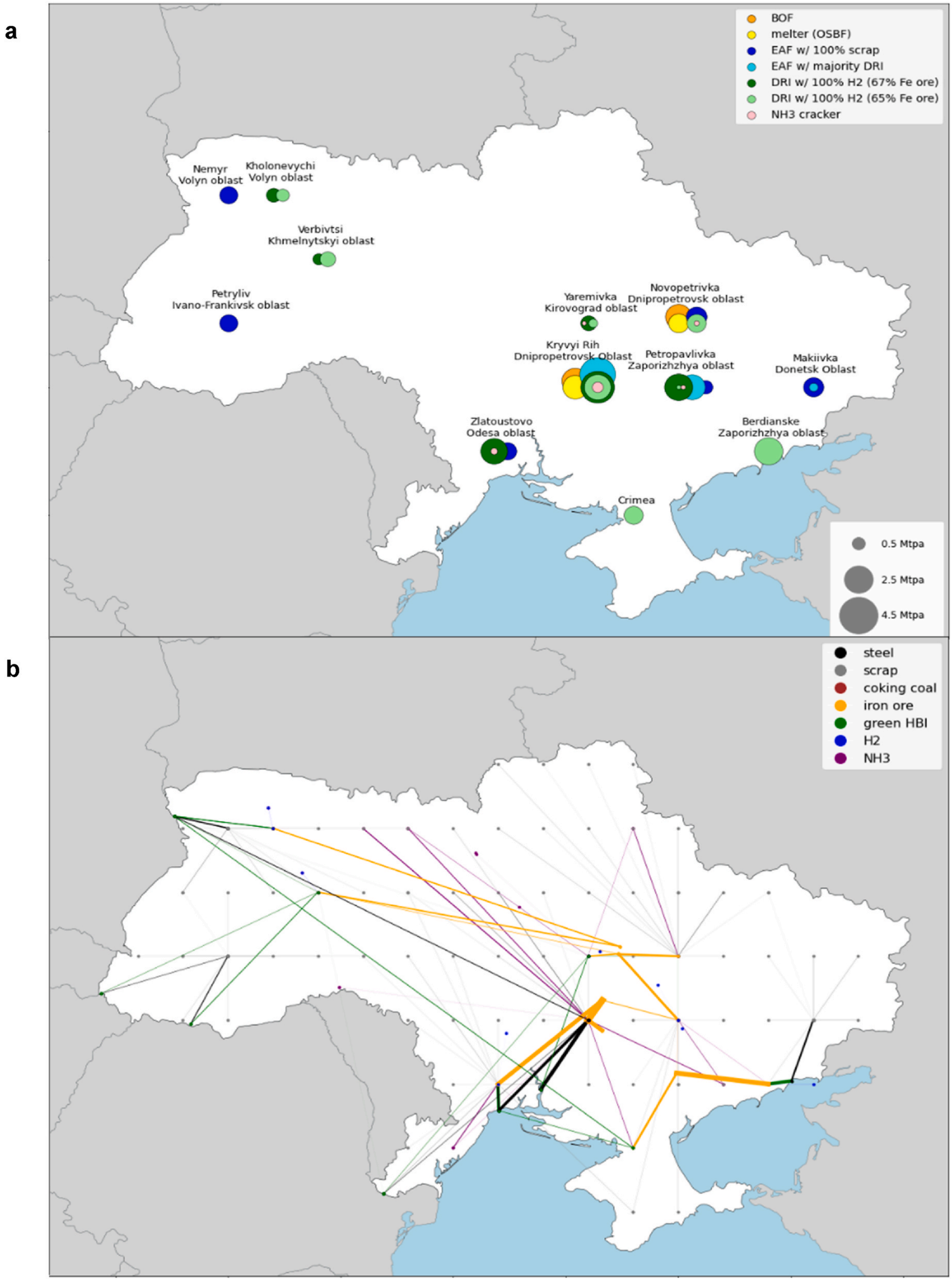

Fig. 4. Optimised steel supply chains in 2050 under the *Strong Recovery* scenario: (a) capacity of iron and steel production assets (colour indicates technology and marker diameter indicates plant capacity), and (b) domestic supply chain flows (straight-line distances shown, line thickness indicates trade volume) including transportation of green steel exports to ports. See SI Figures S1.12 and S1.13 for 2030 and 2040 results, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

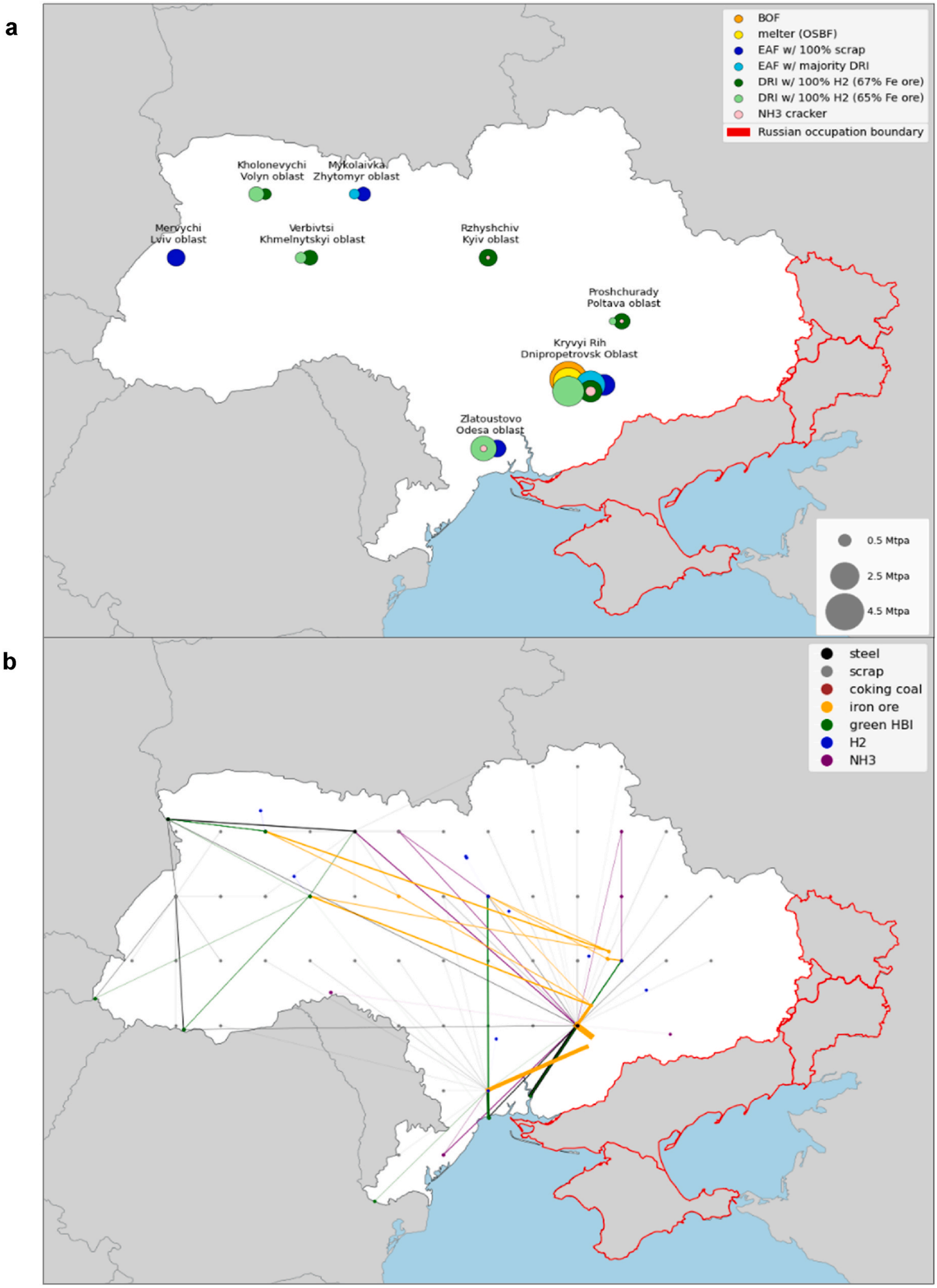

Fig. 5. Optimised steel supply chains in 2050 under the *Slow Recovery* scenario: (a) capacity of iron and steel production assets (colour indicates technology and marker diameter indicates plant capacity), and (b) domestic supply chain flows (straight-line distances shown, line thickness indicates trade volume) including transportation of green steel exports to ports. The geospatial data for Russian-occupied regions are given by DeepState UA (2023), accurate as of April 2023. See SI Figures S1.14 and S1.15 for 2030 and 2040 results, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sector to refrain from gas dependency, aligning with the recent REPowerEU policy (European Union, 2022b) that intends to reduce reliance on Russian gas imports. The immediate period, however, from now until 2030, may benefit from H_2/NG blends, as the price reductions of nascent electrolysis technology is accrued. Cost, rather than supply constraints, is the key determinant of NG redundancy: even without a price on carbon, the NG-DRI-EAF production costs come to $480/t steel based on NG supply at $25/MWh, more expensive than the H_2-DRI-EAF production route with continuous electricity supply at $20/MWh, coming to $430/t steel. In the *Strong Recovery* scenario of 2030, all electrical energy, and the majority (69%) of chemical energy is delivered by onshore solar and wind, whilst the chemical energy gap is filled by nuclear (19%), offshore wind (11%) and hydropower (3%). Moving forward, the expansive capacity of solar and wind is relied on to energise the increase in green steel demand. Tapping into cheap renewables, either locally, via electricity or H_2 supply, or regionally, via NH_3 supply, is critical to competitive green steel production.

4.4. Demand-driven change multiplies cost-effectiveness of green steel investment

Multibillion-dollar industrial investment requires concerted financial support. Simultaneously to rebuild the 22 Mtpa Ukrainian steel industry and transition to near-zero emissions by 2050, the necessary infrastructure investment surmounts to $45.9 billion for renewable energy, $6.6 billion for energy storage, and $9.5 billion for furnaces (i.e., $62 bn in total, given full liberation of Ukrainian territory). Furthermore, the export-oriented industry needs highly efficient railway and sea passage trade routes to attain market competitiveness. Transport is more efficient via shipping vessels; whilst railway infrastructure would need major revitalisation to achieve time and cost efficiencies, including matching Ukraine's railway gauge with that of Europe's, and upgrading capacity to support 9.5 Mtpa of HBI/steel exports. Pipelines must also be installed to deliver 2.6 Mtpa of liquefied NH_3 by 2030, and ports upgraded to manage 6.3 Mtpa of green HBI/steel exports. Ore beneficiation and pelletising capacity must also be bolstered to deliver 9.6 Mtpa of DR-grade ore. Systemic industrial change of this magnitude requires immense mobilisation of capital, for which financial support in the form of carbon prices as well as clean technology incentives is needed. The EU-ETS and CBAM policies are crucial for carbon pricing, but Ukraine also requires significant foreign financial support to drive its industrial transformation and attract private investment.

At the same time, the required steel industry investment will cause ripple effects across the Ukrainian economy. In 2021, for every $1 invested in its basic metals industry, an additional $3.28 was generated elsewhere in the economy through indirect and induced effects (based on the Type II multiplier calculations, see SI Table S1.10). A comparative macroeconomic I-O assessment was undertaken of the: (i) emissions-intensive coal-based steel sector, and (ii) transitioning green steel sector, associated with the three sets - 2030, 2040, 2050 - of *Strong Recovery* and *Slow Recovery* scenarios. Results show that a green steel sector will benefit the economy with stronger supply chain linkages, income generation, and gross value-added under most scenarios. For example, according to the *Strong Recovery* 2050 green steel sector scenario, over its 20-year project lifetime, the Ukrainian economy as a whole is forecast to generate $737 bn of steel sector-driven output, $145 bn of income, and $415 bn of GVA. The corresponding coal-based steel sector would generate less income ($106 bn) and far less GVA ($251 bn). Refer to SI Figure S1.16. The I–O analysis of future green steel production undertaken here is indicative, for it is based on historical compositions of the traditional electricity and chemical industries. Growing renewables shares in the electricity sector and electrolytic processes for H_2 and NH_3 production will transform the way these sectors interact with the wider economy, and perhaps even bolster the forward and backward linkages involved. Nevertheless, a strong relationship between the proposed green steel sector transition and (much) faster economic growth is determined. The structural transformation of the mining and metals industries into a value-adding green steel sector will return far-reaching economic benefits, stimulating employment, supply chain expenditure, and sustainable export revenues. Refer to SI Figure S1.16 and SI Section S2.4.4 for details about all the modelled scenarios.

5. Conclusions

This study explores tensions between optimism and realism to assess possibilities for Ukraine to build back greener in its steel sector. Transitioning from a coal-dependent to renewables-dependent steel industry is feasible, given clear climate policies, strong regional trade links, and access to capital. Multiple factors favour Ukraine's green steel potential: valuable iron ore resources, reasonable solar irradiation and wind speeds, large land mass, high-flowing rivers to support cheap hydropower, uranium resources to support nuclear power, low wages, and proximity to EU green steel markets via ports and railways. Prospective EU accession makes steel decarbonisation non-negotiable, whilst opening critical green export markets. Moreover, whilst the core capital investment needed for Ukraine's green steel transition amounts to $62bn over a 20-year period (excluding the required connectivity upgrades), a green steel sector alone will generate $164bn worth of additional GVA more than the corresponding coal-based steel sector, *ceteris paribus*.

A mixed energy portfolio will balance the intermittency of renewables across time and space: solar, wind (onshore and offshore), hydro, and nuclear, among other sources, can contribute to the integrated fossil-free energy system. There are multiple pathways to near-zero emission by 2050, and no single technological solution is ideal. The results shown here encompass H_2-DRI-EAF, H_2-DRI-melter-BOF, and scrap-based production routes, though emerging solutions like direct iron ore electrolysis may also play a role in the EAF technology mix once they reach maturity. Greenfield plant sites take advantage of the cheapest renewables available. Although brownfield sites benefit from established transport links and local skilled labour pools, these are diminished in a post-war context, where significant infrastructure destruction has occurred, and steel-making communities dislocated. Managing risks associated with fossil fuel asset 'lock-in' (i.e., emission inertia caused by physical and economic constraints) and stranded assets (i.e., infrastructure that becomes redundant before the end of its anticipated economic lifetime) are critical in the steel sector's decarbonisation pathway, given the industry's capital-intensity and long amortisation periods.

The results transcend the Ukrainian context (21.4 Mt steel produced, 15.7 Mt exported in 2021) to other iron ore-producing nations with export-oriented steel industries: for example, Brazil (36.2 Mt steel produced, 11.5 Mt exported) and Vietnam (23.0 Mt steel produced, 11.2 Mt exported) (World Steel Association, 2022). In future work, the supply chain optimisation model can be modified for any geographical context and spatial scope. Significant efforts were made to utilise Ukraine-specific resource constraints, geospatial data, renewable energy infrastructure costs, commodity prices, carbon prices, domestic steel demand, and green iron/steel export projections, which must be modified for each specific case. Flexibility within the integrated energy system could be explored further, for example, regarding the use of dispatchable nuclear/hydro in lieu of battery/CGH_2 storage for renewables. To share some preliminary insights, it was deduced that flexible H_2-DRI-EAF production with up to 25% dispatchable power allowance at $25/MWh reduced the LCOS by 27%. Finally, this work did not address environmental and social issues beyond climate change; a holistic sustainability impact assessment framework should be developed for the green steel industry.

Code availability

GAMS code developed in this study for the steel production and trade optimisation model is available online, alongside the input data files (https://doi.org/10.25446/oxford.24146466.v1). The code developed for the renewable electricity, green H_2, and green NH_3 production is also available online (https://github.com/nsalmon11/LCOH_Optimisation).

CRediT authorship contribution statement

Alexandra Devlin: Conceptualization, Funding acquisition, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Vlad Mykhnenko:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Anastasiia Zagoruichyk:** Investigation, Writing – original draft. **Nicholas Salmon:** Investigation, Methodology, Software. **Myroslava Soldak:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

See the Code Availability and Supplementary Information files.

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Appendix A. Supplementary Information

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142675.

Abbreviations and Chemical Notation

BF	Blast Furnace
BOF	Basic Oxygen Furnace
CBAM	Carbon Border Adjustment Mechanism
CO_2	Carbon dioxide
DRI	Direct Reduction of Iron
EAF	Electric Arc Furnace
ETS	Emissions Trading Scheme
EU	European Union
GDP	Gross Domestic Product
GVA	Gross Value Added
H_2	Hydrogen
HBI	Hot Briquetted Iron
LCOA	Levelised cost of ammonia
LCOE	Levelised cost of electricity
LCOH	Levelised cost of hydrogen
LCOS	Levelised cost of steel
NG	Natural gas
NH_3	Ammonia
NPV	Net Present Value
OHF	Open Hearth Furnace
OSBF	Open Slag Bath Furnace
RE	Renewable energy
SI	Supplementary Information

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