Green steel will turbocharge Ukraine's post-war recovery

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 emerging markets and unstable socio-political contexts. A new University of Oxford study by **Alexandra Devlin**, **Vlad Mykhnenko** and their colleagues provides a blueprint for reconfiguring plant locations and reallocating resources through a Ukrainian case study, which captures alternative post-war conditions.[1]

Much of Ukraine's pre-war steel production capacity has been destroyed. Reconstructing Ukraine will require vast amounts of steel, which should be locally produced to stimulate the post-war recovery and economic growth. The projected domestic demand for steel, in addition to perceived export demands for green iron and steel from nearby European markets, should provide the steady demand signal required for investment (**Fig 1**). Rebuilding Ukraine's ravaged steel sector - once hostilities cease - presents a golden opportunity to harness the long-term economic benefits of low- to near zero-emissions steelmaking.

Before the Russian large-scale invasion, Ukraine was the 14th largest global steel producer, with 21.4 million tonnes of steel output in 2021, two-thirds of which - $16 billion worth - destined for exports. Yet, the nation produces some of the world's most emissions-intensive steel at 2.3 tonnes of CO_2 per tonne of steel (t CO_2/t steel) on average – *the worst* ranking of 17 studied nations and territories, responsible for 48 Mt CO_2 or 15% of Ukraine's CO_2emissions in 2020.

Ukrainian steelmakers are deeply dependent on coal-based blast furnaces (BF), and ongoing use of outdated open-hearth furnaces (OHF), which have been substituted widely by the more efficient basic oxygen furnace (BOF).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. The average emissions-intensity for the iron ore-based BF route was 2.41 t CO_2/t steel, and 0.77 t CO_2/t steel for the scrap-based EAF route.

Near zero-emissions or 'green' steel could offer a practical way forward towards the long-term climate neutrality goal that revitalises Ukraine's economic activities and supports its expanding defence industries. Green steel could also emerge as an export and investment catalyst, necessitating focused investment in adaptable and innovative production capacities.

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.

[1] The full report on 'Techno-economic optimisation of steel supply chains in the clean energy transition: A case study of post-war Ukraine' can be found via this link: https://doi.org/10.1016/j.jclepro.2024.142675

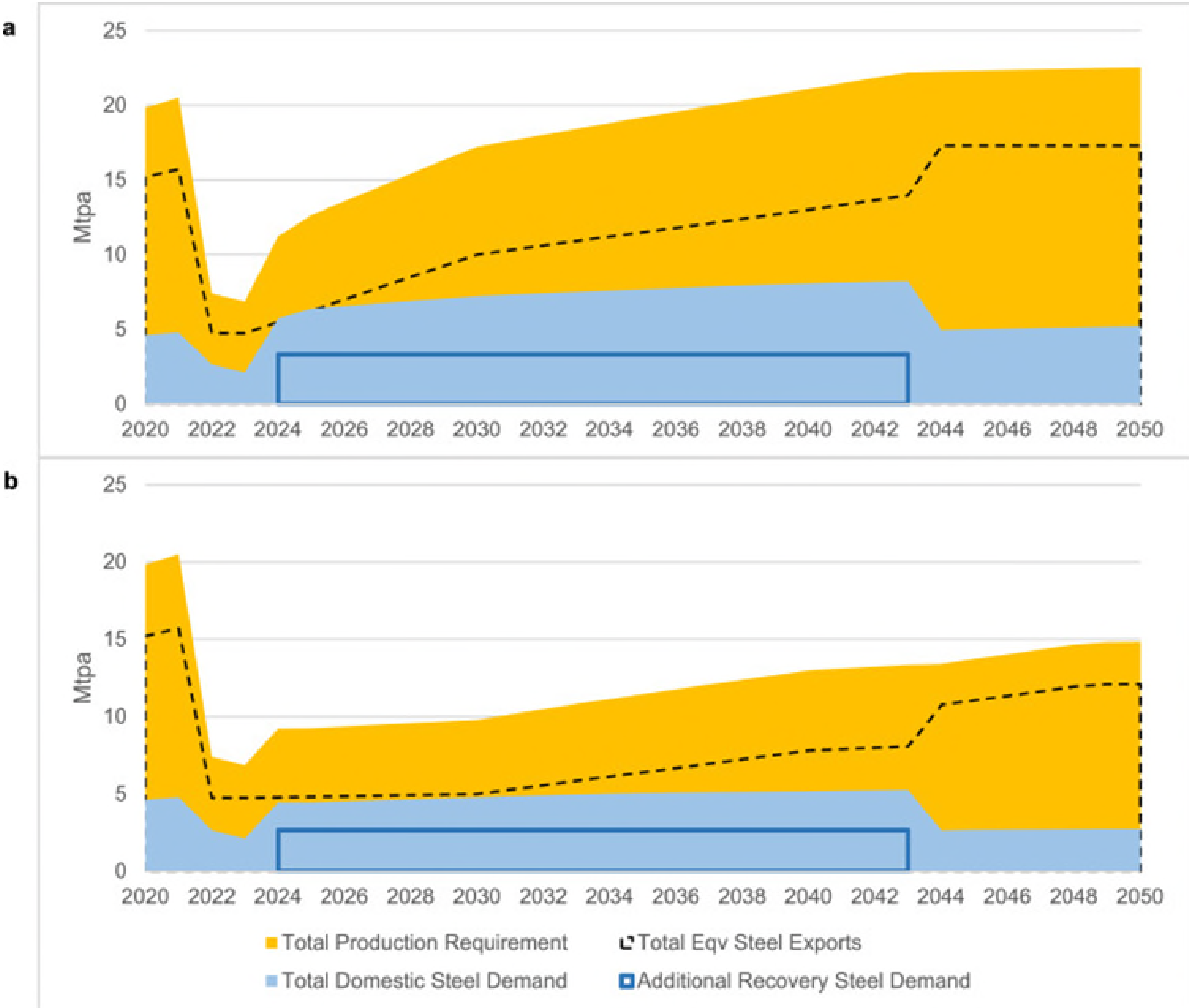

Figure 1 Ukraine steel demand projections, inclusive of exports, domestic consumption, and additional reconstruction needs, for the (a) *Strong Recovery* scenario (including full liberation and rapid EU accession), and (b) *Slow Recovery* scenario (partial liberation and slow EU accession), respectively. Exports are a combination of green hot briquetted iron (HBI) and green steel, expressed as steel equivalents, in million tonnes per year (Mtpa).

The economic case for Ukraine using renewables in steel production is underpinned further by the impending European Union (EU) membership requirements. 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 is currently established at around \$100/t CO_2 and is forecast to increase to \$250/t by 2050, without any free allowances. Moreover, the 'EU Green Deal' targets commercialisation of near-zero emissions steel by 2030, and full decarbonisation of the sector by 2050. This makes Ukraine's steel decarbonisation non-negotiable. Thus, Ukrainian steelmakers must prepare for this impending transition.

A variety of technologies within the steel production process can reduce industrial emissions. The simplest pathway forward to achieve decarbonisation is to switch to scrap-based EAF production, and power operations using renewable energy. However, Ukraine's end-of-life steel scrap resources are constrained by historical steel consumption, which may slightly increase over the coming decades, but are highly uncertain due to the effects of war (whilst the destruction has increased the quantity of end-of-life scrap resources, the radioactive nature would deem these resources futile). The country will still largely depend on iron ore-based steel production, which involves the harder-to-abate iron production process. 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. 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 (expected by 2026).

High-quality renewable energy, that produces cheap CO_2-free electricity and hydrogen, underpins the business case for green H_2-based steel production. Though no clear consensus has formed in the literature so far regarding the best hydrogen carrier, green ammonia (NH_3) is a viable potential derivative. 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.

A spatially granular approach was undertaken to assess renewable energy and steel production potential. 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 was decentralised - each grid could produce its own renewable power – whilst energy availability was interconnected – each grid could import electricity/H_2/NH_3 from other grids. A range of CO_2 free energy sources were considered - green commodities (electricity, H_2 and NH_3) could be sourced from onshore hybrid solar/wind, offshore wind, nuclear or hydropower plants (with availability constrained by available natural resources (in the case of renewables) and/or existing assets (in the case of mature nuclear and hydropower).

Building on green H_2-DRI-EAF optimisation modelling competencies from previous studies, this research includes 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). Two potential post-war geographies were assessed under scenario analysis - full restoration of the nation's territorial integrity with rapid EU accession (*Strong Recovery*) and partial liberation with delayed EU accession (*Slow Recovery*).

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 was estimated. Favourably, Ukraine's green LCOS range in ideal locations was calculated to be \$440–600/t. The lower end represents H_2-DRI-EAF production with 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 H2), using new-build onshore hybrid solar and wind power (**Fig 2**).

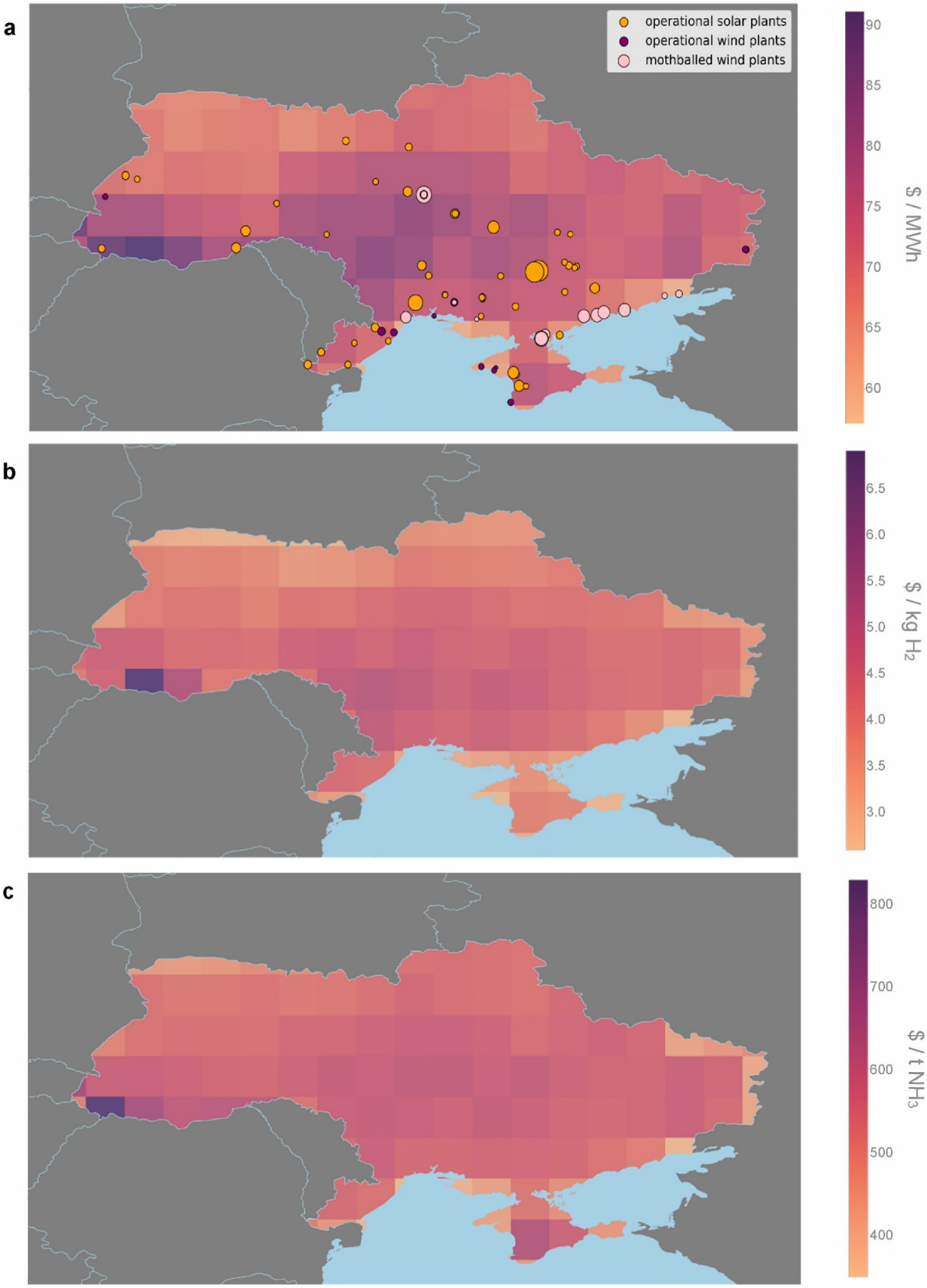

Figure 2 Cost-minimised results of onshore hybrid solar and wind plant energy products installed in 2050: (a) Levelised cost of firm electricity (in USD/MWh), plotted with existing solar and wind

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).

The decoupling of iron and steel production with the switch from integrated BF-BOF production to separable DRI-EAF production introduces a critical export opportunity for Ukraine. In a decarbonised production system, cost-competitive green HBI is directly dependent on the price of CO_2-free electricity. About 75% of the costs of steelmaking occur up to the point of iron production due to its energy-intensive nature. With electricity costs of $64/MWh (representing cost-competitive continuous renewables), the levelised cost of green HBI is estimated at $440/t. With cheaper firm electricity of $20/MWh, costs will reduce to $290/t which is very competitive with green HBI costs estimated for other ore-producing regions, e.g., $395/t in South Africa, especially considering the reduced transportation costs. Tapping into high quality renewables, and supplementing with cheaper mature CO_2-free resources (i.e. hydropower and/or nuclear power) is essential for HBI and steel cost reduction in Ukraine, and export market retention.

To transition to a green steel industry, no new fossil-fuel dependent furnaces should be installed. All new capacity must be near-zero emissions compatible – that is, operations that can reach near-zero emissions over time, given a reliable supply of CO_2-free energy inputs. 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 (**Fig 3**), 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.

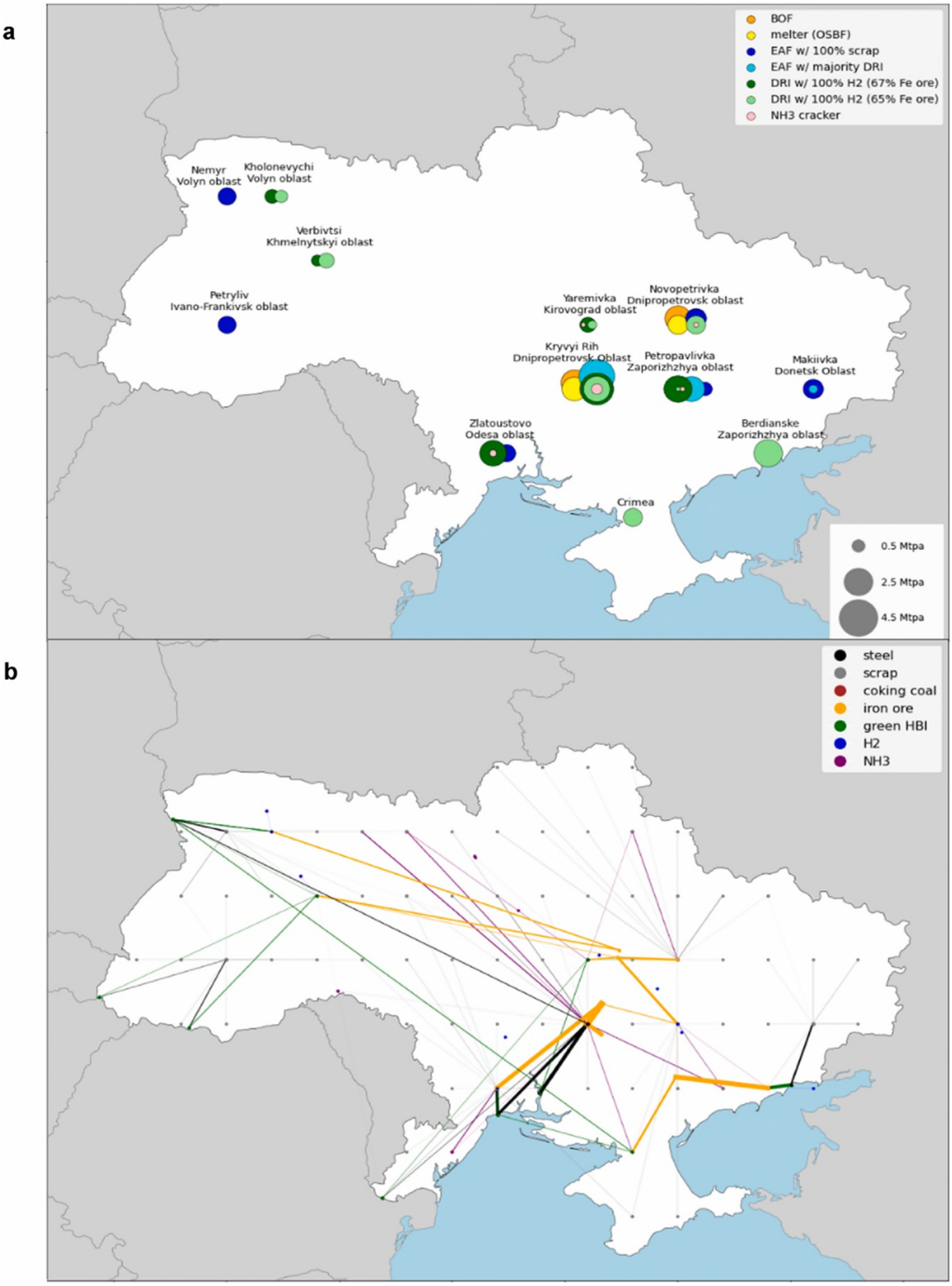

Figure 3 Optimised steel supply chains in 2050 under the *Strong Recovery* scenario: (a) capacity of iron and steel production assets (colour indicates technology and marker diameter indicates plant capacity), and (b) domestic supply chain flows (straight-line distances shown, line thickness indicates trade volume) including transportation of green steel exports to ports.

For a full green steel production transformation, Ukraine would require investment of $62 billion over 20 years. This capital injection would cover $45.9 billion for renewable energy infrastructure, $6.6 billion for energy storage, and $9.5 billion for iron and steelmaking furnaces, in addition to funds to recover and upgrade the supporting transportation systems.

The study stresses that a robust green steel sector in Ukraine would have ripple effects across the entire economy, for instance, through stronger supply chain links. In 2021, for every $1 invested in Ukraine’s basic metals industry, an additional $3.28 was generated elsewhere in the economy. Replacing coal as the main heating source in steel furnaces with renewable energy will radically accelerate economic growth. By 2050, a green steel pathway would generate up to $415 billion worth of gross value added (GVA) in total; or $164 billion (1.7 times) more than equivalent investment based on traditional coal-based steelmaking.

As a positive step forward, a recent commitment by domestic players (including Metinvest and ArcelorMittal) of $35bn into the medium-term green steel transition strategy until 2035 means the outstanding amount needed would be significantly lower.

The vast destruction of Ukraine's iron and steelmaking assets represents a stark opportunity to rebuild a thriving industrial sector which is independent of fossil fuels. Ukraine is well positioned to supply European green steel markets, which will provide employment throughout the value chain, and deliver returns to the economy well beyond the original investments.