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BUILDING A GREEN, FAIR AND RESILIENT SOLAR SUPPLY CHAIN

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Project Europe 2050

ANALYSIS

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Preface by the editors

Europe stands at a critical juncture in its energy strategy, facing opportunities and challenges that demand a nuanced approach. It currently has a window of opportunity to both diversify its energy supply and strengthen its independence through new globalized partnerships. However, this transition is not without its risks, given the existing constraints of Europe's energy infrastructure and its geographic location.

The opportunities and challenges both also concern Europe's green strategy alike. Since the onset of Russia's war against Ukraine, the disruption of pipeline-bound gas trade has led to a resurgence of CO2-intensive fuel sources like lignite, while natural gas consumption has been scaled down. Simultaneously, there is a growing consensus on the need to prioritize renewable energy generation, with initiatives like the EU Green Deal. However, Europe faces substantial differences among member states in their energy and climate strategies, coupled with infrastructural and economic bottlenecks. This divergence still leaves Europe struggling to make a decisive shift toward a more sustainable energy infrastructure.

When it comes to specific components of this critical infrastructure, such as solar panels, which are the focus of this study, China's monopolies in the renewable energy sector pose a unique challenge of its own. Whilst a deviation of supply chains for renewable power sources may decrease political coercion risks, China's dominance in the production of renewable energy technologies, which also include wide-ranging capacities in the mining, smelting, and refinement industries that Europe does not have, creates a densely integrated power lever that continues to keep Europe under pressure even if it successfully de-risks in single key technologies.

That said, re-globalising supply chains for key technologies remains the way to go. Not only does Europe depend on imports that it can no longer rely on China to provide exclusively, but because its geographical positioning creates specific vulnerabilities, namely critical trade routes like the Suez Canal and the Strait of Hormuz, which expose it to potential disruptions of its international trade routes in general, not only for specific tech components. A diversification of stable collaborations, that are not only reliable in the long-term, but also geographically distributed throughout the globe, therefore helps alleviate a risk that is much greater than that of Europe's energy transition alone.

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Executive Summary

→ **The global solar PV supply chain is deeply dependent on the People's Republic of China (PRC):** The PRC's global market share across the whole solar PV supply chain exceeds 80%, and stretches to over 97% at the silicon wafers stage of production.

→ **Dependence on PRC solar undermines energy security and puts Net Zero targets at risk:** The PRC has a track record of weaponizing its dominance of critical supply chains to achieve geopolitical goals. This threatens the UK's target to ramp up solar capacity fivefold by 2035, and puts at risk a major component of the UK's future energy supply.

→ **PRC solar sanctions could impose major costs on UK energy bills:** Our modelling shows that PRC bans on solar exports, for example, precipitated by geopolitical fallout following a conflict across the Taiwan strait, could cost the UK £4.40 billion by 2035 in increased energy bills, or £155 per household and provide a major setback to the UK's climate ambitions, with new solar installations falling far behind planned targets.

→ **The UK needs a new solar strategy:** The UK finds itself in a precarious position when it comes to securing the solar PV supply chain. Unlike the US and EU, the UK has no major solar manufacturing capacity to scale up. This paper proposes a UK solar strategy based on three priorities:

- ***De-risking new solar installations:*** The UK should incentivise its energy providers to diversify their supply chains by introducing minimum standards of supply chain resilience as a precondition for government support, including for new bids under the Contracts for Difference scheme. Standards should ensure that UK providers are not overly reliant on the PRC's supply chain and have effective contingency plans for supply chain disruptions.

- ***Diversifying the global supply chain:*** Vietnam, Malaysia, and other countries in Southeast Asia are best placed to compete with the PRC's economies of scale and low energy costs – particularly at the earlier stages of the solar PV supply chain. The UK should press for the G7's Partnership for Global Infrastructure and Investment to raise US $5bn for large-scale capacity building at the strategically important polysilicon and wafers stages of production.

- **Investing in leading-edge technologies:** Perovskite solar cells have emerged as a promising alternative to traditional crystalline silicon panels, being both more efficient and less dependent on the PRC's polysilicon supply chain. UK firms and universities lead the world in the research and development of PSCs, an advantage that can be cemented with further government support.

1. The PRC's role in the solar PV supply chain

1.1 Introduction

The last decade has seen a major reorientation of global solar PV supply chains. While once dominated by the US, Japan, and Europe, firms belonging to the People's Republic of China (PRC) have emerged as today's preeminent market leaders. The PRC is the world's leading manufacturer at each stage of the solar PV supply chain, with its global market share across the whole value chain exceeding 80%.[1]

This surge in the PRC's production capacity is part of an intentional, decades-long push by the PRC government. The State Council named solar a "strategic emerging industry" in 2010 and has since promoted the sector with generous subsidies and fast-tracking the myriad of necessary bureaucratic procedures from land acquisition to industrial permits.[2] The PRC has invested over US $50 billion in new PV supply capacity since 2011 – ten times more than Europe across the same period.

This section unpacks the PRC's dominance at each stage of the solar PV supply chain, analysing how and why PRC firms are outperforming their international peers.

1.2 Unpacking the solar PV supply chain[3]

The vast majority of solar panels are made up of polysilicon-based crystalline silicon cells, with the remainder being predominantly thin-film cadmium telluride cells. This section will focus predominantly on polysilicon-based panels, which account for over 95% of global production.[4]

The solar PV supply chain can be structured into six distinct stages. The process begins with the extraction and refinement of raw materials. Crucially, quartz rock (silica; SiO_2) is mined from the earth and reduced to produce metallurgical-grade silicon. Metallurgical-grade silicon (MGS) is further refined to produce solar-grade polysilicon with a higher level of silicon purity. The next phase sees polysilicon turned into large cylinders (called ingots), which in turn are precision-sliced into thin wafers. These early stages of production are energy-intensive and require large amounts of electricity. At the later stages, wafers undergo a sophisticated treatment regimen, culminating in the creation of photovoltaic cells capable of harvesting and converting sunlight into electrical energy. Finally, individual cells are assembled into panels by being encased within protective materials, resulting in fully assembled solar panels.

Figure 1 | Production of solar panels

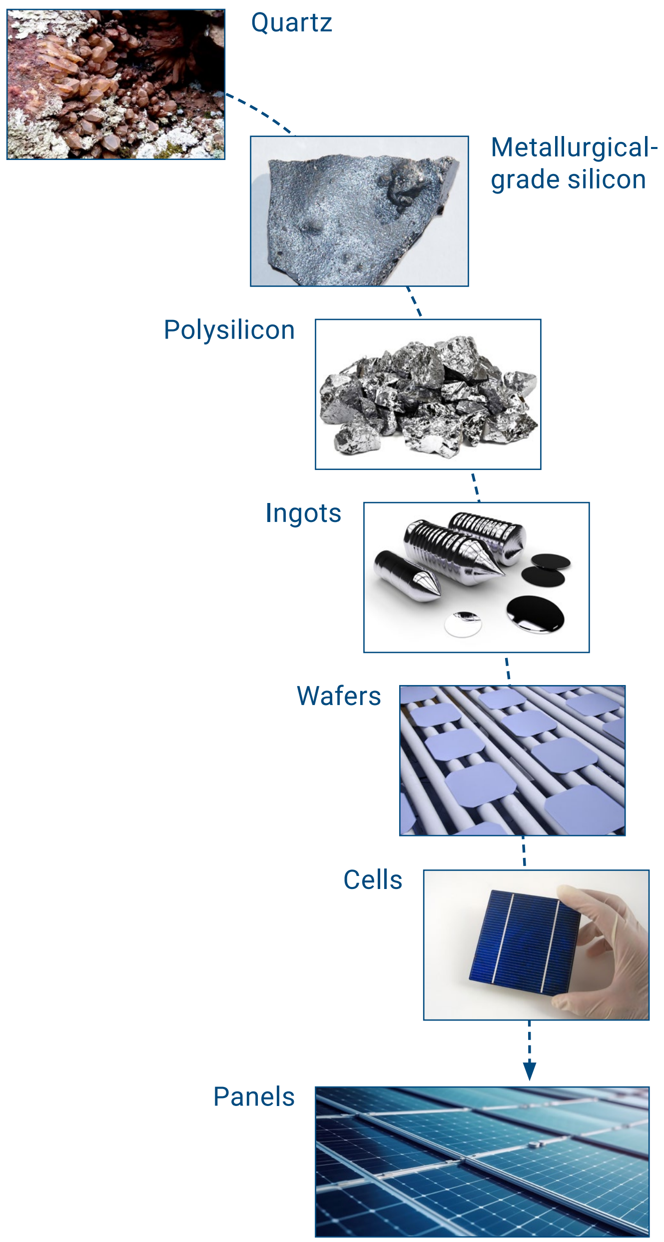
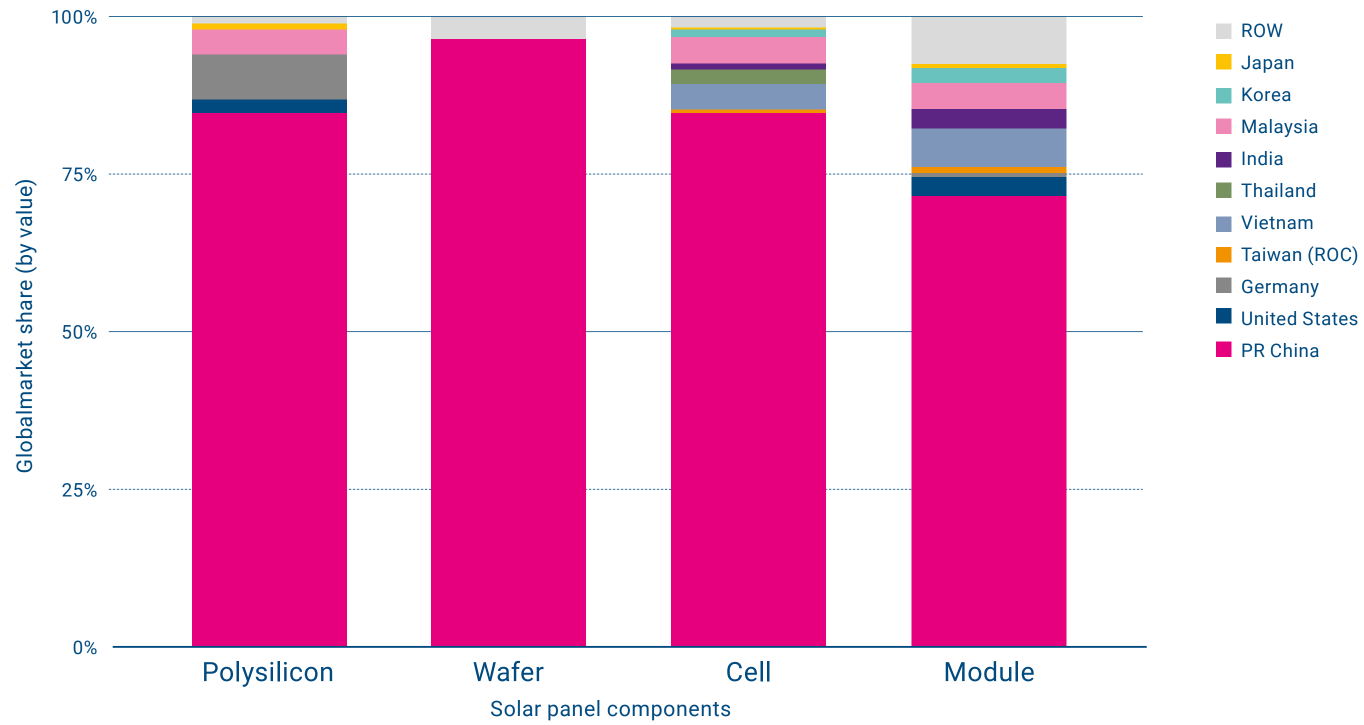


Figure 2 | Global market share of polysilicon, wafer, cell and module by value



Data source: IEA (2022), Solar PV Global Supply Chains, IEA, Paris. Reproduced with permission.

Metallurgical-grade silicon, polysilicon and raw materials

The PRC dominates global MGS production, with approximately 80% of the world's output.[5] Polysilicon, the next stage in the value chain, makes up 35 - 45% of the average value of the finished solar panel.[6] The PRC is also the leader at this stage, responsible for over 80% of solar-grade polysilicon in 2021. The PRC's market share is expected to increase further as hundreds of thousands of metric tonnes in additional capacity are slated to come online.[7]

The concentration of MGS and polysilicon production in the Xinjiang Uyghur Autonomous Region (XUAR) raises significant ethical concerns. Approximately 35% of global polysilicon and 44% of the PRC's total MGS output is produced in the XUAR.[8] State-sponsored forced labour is endemic to the XUAR and is present in practically all industrial activity in the region. Since 2016, the PRC government has interned upwards of one million Uyghurs and other minority ethnic and religious groups in the XUAR in so-called 'vocational training centres', with many detainees required to work at commercial factories built within or near the detention facility. Additionally, the PRC government has enlisted 2.6 million Uyghurs and other minority groups in 'labour transfer schemes', which send workers to farms and factories in the region or elsewhere in the PRC.[9] MGS and polysilicon produced in the region are also used by solar manufacturers elsewhere in the PRC, meaning that forced labour concerns are not restricted to the XUAR alone. While some manufacturers have shifted their polysilicon procurement to Inner Mongolia and other regions in the PRC, the MGS used in the production of polysilicon is still likely to be from XUAR.

Ingots and Wafers

Wafers are the most geographically concentrated segment of the solar PV supply chain, with the PRC holding 96.8% of global production capacity in 2022.[10] This dominance means that all subsequent stages of the supply chain are heavily dependent on the PRC's wafer production. This trend looks set to continue, with the PRC wafer manufacturers announcing plans to add a further 300 GW of capacity by 2024.[11]

1 International Energy Agency, Special Report on Solar PV Global Supply Chains (OECD, 2022), 7, https://doi.org/10.1787/9e8b0121-en.
2 US-China Business Council, 'China's Strategic Emerging Industries: Policy, Implementation, Challenges, & Recommendations' (US-China Business Council, March 2013), https://www.uschina.org/sites/default/files/sei-report.pdf.
3 Constantine Shovel, *Comb Quartz from Montiferru*, 23 February 2019, 23 February 2019, Own work, https://commons.wikimedia.org/wiki/File:Comb_quartz_from_Montiferru.jpg; Hi-Res Images of Chemical Elements, *Pure Silicon, Rough Surface*, 2 Grams, Size 2 Cm, 20 December 2009, 20 December 2009, http://images-of-elements.com/silicon.php, https://commons.wikimedia.org/wiki/File:Pure_Pure_silicon,_rough_surface,_2_grams,_size_2_cm.jpg; Bjorn Wylezich, *High Purity Polycrystalline Silicon from Freiberg*, Germany Isolated on White Background Stock Photo, accessed 30 October 2023, https://stock.adobe.com/uk/images/high-purity-polycrystalline-silicon-from-freiberg-germany-isolated-on-white-background/191755963; frog, *Silicon Ingot Stock Illustration*, accessed 30 October 2023, https://stock.adobe.com/uk/images/silicon-ingot/47721432; Oregon Department of Transportation, *Wafers on the Conveyor*, 24 February 2009, 24 February 2009, Wafers on the conveyor Uploaded by Smallman12q, https://commons.wikimedia.org/wiki/File:Wafers_on_the_conveyor_(3346902863).jpg; Albert Lozano-Nieto, Solar Cell Research Stock Photo, accessed 30 October 2023, https://stock.adobe.com/uk/images/solar-cell-research/1000792.
4 International Energy Agency, Special Report on Solar PV Global Supply Chains, 13.
5 'Everything You Need to Know about China's Industrial Silicon Market_SMM | Shanghai Non Ferrous Metals', SMM, 6 February 2023, https://news.metal.com/newscontent/102084821/Everything-You-Need-to-Know-about-China%E2%80%99s-Industrial-Silicon-Market/; Sadhna Gupta, 'Exploring the Factors Behind Volatility in the Silicon Market', Aranca, 28 April 2023, https://www.aranca.com/.
6 International Energy Agency, *Special Report on Solar PV Global Supply Chains*, 21.
7 Johannes Bernreuter, 'Tongwei and Xinte to Upgrade Polysilicon Production Capacities', 29 April 2021, https://www.bernreuter.com/newsroom/polysilicon-news/article/tongwei-and-xinte-to-upgrade-polysilicon-production-capacities/.
8 Alan Crawford and Laura T. Murphy, 'Over-Exposed: Uyghur Region Exposure Assessment for Solar Industry Sourcing' (Sheffield, UK: Sheffield Hallam University Helena Kennedy Centre for International Justice, 2023), 2, https://www.shu.ac.uk/helena-kennedy-centre-international-justice/research-and-projects/all-projects/over-exposed.
9 Laura T. Murphy and Nyrola Elimä, 'In Broad Daylight: Uyghur Forced Labour and Global Solar Supply Chains' (Sheffield, UK: Sheffield Hallam University Helena Kennedy Centre for International Justice, 2021), https://www.shu.ac.uk/helena-kennedy-centre-international-justice/research-and-projects/all-projects/in-broad-daylight.
10 International Energy Agency, Special Report on Solar PV Global Supply Chains.
11 International Energy Agency, 24.

This not only increases the PRC's dominance of the supply chain, but also discourages potential competitors by flooding the market. A further challenge is that the PRC is also the main producer of the machinery required to slice polysilicon ingots into wafers. PRC firms have made significant advances in slicing bigger and thinner wafers, allowing solar panels to make major efficiency and cost gains in recent years.[12]

Cells and Modules

While the PRC remains the undisputed global leader at the cell stage of production – accounting for approximately 82% of global solar cell manufacturing capacity – other countries are playing an increasingly important role.[13] Southeast Asian countries, including Vietnam, Malaysia, and Thailand, have all expanded production capacity in recent years. Together with Korea, Southeast Asian countries now account for 18% of the global cell market.[14] However, it is important to note that much of the investment in Southeast Asia's cell production capacity has been led by PRC firms using PRC upstream inputs, often with a view to circumvent US import tariffs and the US Uyghur Forced Labour Prevention Act.[15] To take full advantage of Southeast Asia's growing solar manufacturing capacity, more investment is needed to increase local production of upstream inputs – a recommendation returned to later on in this paper.

The PRC also leads the world in module manufacturing, with 70% of global production capacity. However, its lead is less pronounced compared to other stages of the supply chain. While the polysilicon, wafers and cells stage of the supply chain sees significant benefits from economies of scale, modules can be manufactured profitably in smaller batches and do not entail as high capital investment. This means that module assembly is the most geographically diversified stage of the solar PV supply chain, with 38 countries possessing module assembly capabilities in 2021. Aside from the PRC, the largest manufacturers by global market share are Vietnam (5%), Malaysia (4%), Korea (4%) and the United States (4%).[16]

1.3 Why is the PRC so dominant?

Low energy costs

An important factor in the PRC's dominance of the solar PV supply chain is its low energy costs. This is particularly relevant at the early stages of the supply chain, where the energy-intensive extraction processes for metallurgical-grade silicon, polysilicon and other raw materials make the PRC an ideal producer. Energy costs contribute to approximately 40% of a polysilicon factory's operating costs.[17] Average industrial electricity costs for businesses in the PRC are priced at US $0.087/kWh, which is 37.6% of the UK equivalent (US $0.230/kWh) and 42.3% of the German equivalent (US $0.205/kWh).[18] More specifically, cheap energy in the provinces of Yunnan, Sichuan, Inner Mongolia and the XUAR make them ideal locations for developing new solar manufacturing capacity.[19] The dependence on coal-generated electricity in the XUAR for MGS and polysilicon production has serious environmental implications, with a carbon footprint nearly four times larger than solar panels manufactured with cleaner energy in Europe.[20] The PRC is likely to retain its competitiveness on energy prices over the US and Europe due to its willingness to maintain coal as the main source of its electricity generation, rather than more expensive, greener fuels, and its comparatively low tax on energy costs.[21]

Economies of scale

Economies of scale describe the cost advantages achieved when producing a good in large quantities. PRC firms have been able to achieve economies of scale by receiving significant government support in raising high levels of capital investment to finance large-scale solar production. Economies of scale are particularly important at the early stages of the supply chain. For instance, greenfield polysilicon plants are not usually bankable for capacities of less than 3 GW, while recent plants in the PRC range in size from 40,000 Mt to 100,000 Mt, almost tripling historical averages.[22] Further, the presence of large-scale production at all stages of the supply chain in the PRC has also allowed PRC manufacturers to benefit from vertical supply chain integration, with simplified logistics across the supply chain. These reduced costs have allowed PRC firms to undercut foreign rivals and dominate the global market.

12 Dan Murtaugh, 'China Mulls Protecting Solar Tech Dominance With Export Ban', Bloomberg.Com, 26 January 2023, https://www.bloomberg.com/news/articles/2023-01-26/china-mulls-protecting-solar-tech-dominance-with-export-ban.
13 International Energy Agency, Special Report on Solar PV Global Supply Chains, 18.
14 International Energy Agency, 26.
15 Crawford and Murphy, 'Over-Exposed: Uyghur Region Exposure Assessment for Solar Industry Sourcing'.
16 International Energy Agency, Special Report on Solar PV Global Supply Chains, 27.
17 Dan Murtaugh et al., 'Secrecy and Abuse Claims Haunt China's Solar Factories in Xinjiang', Bloomberg.Com, 13 April 2021, https://www.bloomberg.com/graphics/2021-xinjiang-solar/.
18 Department for Energy Security & Net Zero, 'Energy Prices International Comparisons - Industrial Electricity Prices in the IEA', 28 September 2023, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1187781/table_531.xlsx; CEIC, 'China | Price Monitoring Center, NDRC: Transaction Price: Production Material: Electricity | CEIC', accessed 8 November 2023, https://www.ceicdata.com/en/china/price-monitoring-center-ndrc-transaction-price-production-material-electricity.
19 Bloomberg News, 'China's Solar Industry Is Slowly Shifting Away From Xinjiang', Bloomberg.Com, 21 December 2021, https://www.bloomberg.com/news/articles/2021-12-21/china-s-solar-industry-is-slowly-shifting-away-from-xinjiang.
20 Seaver Wang and Juzel Lloyd, 'Sins of a Solar Empire' (Breakthrough Institute, 15 November 2022), 29, 35.
21 Jeromin Zettelmeyer et al., 'Beating the European Energy Crisis', International Monetary Fund, December 2022, https://www.imf.org/en/Publications/fandd/issues/2022/12/beating-the-european-energy-crisis-Zettelmeyer.
22 International Energy Agency, *Special Report on Solar PV Global Supply Chains*, 85.
23 US-China Business Council, 'China's Strategic Emerging Industries: Policy, Implementation, Challenges, & Recommendations'.

Relaxed regulations

Solar production, particularly at the polysilicon and raw minerals stage, involves energy-intensive and infrastructure-heavy ventures with high levels of safety risks, pollution and environmental impact. Compared to demanding safety, environmental and planning regulations in the US, Europe, Japan and elsewhere, solar producers in the PRC have benefited from less stringent safety and environmental regulations and the fast-tracking of the myriad of necessary bureaucratic procedures from land acquisition to industrial permits.[23] For these reasons, the PRC's new polysilicon plants have had some of the world's shortest lead times for construction – as low as 12 months compared to a global average of three years.[24] Significant differences in the PRC design standards mean that polysilicon plants designed for the PRC could not be directly replicated in other parts of the world with stricter regulations.

2. Why is the solar PV supply chain a strategic risk?

2.1 Solar and the UK's energy security

Expanding domestic solar power generation is a key component of the UK government's commitment to achieving fully decarbonised electricity by 2035.[25] Government strategy documents make it clear that solar power is key to both meeting the UK's 2050 'Net Zero' target and achieving greater energy security – the latter issue brought to the fore by the impact of Russia's invasion of Ukraine on global energy markets.

While solar currently only makes up 4.4% of the UK's electricity generation, current UK government plans aim to scale up to 70 GW of solar power capacity by 2035.[26] This amounts to a five-fold increase in current installed capacity, with solar energy projected to make up between 6% and 8% of the UK's electricity mix.[27] While this amount may appear small, the costs of failing to meet this planned expansion of solar capacity are very high. This is due to solar energy being significantly cheaper than other energy sources – as demonstrated by our modelling in the next section.

Expanding solar capacity is intended to increase the UK's economic resilience. Domestic solar capacity reduces the need for imported energy and thus makes the UK less exposed to shocks in global energy markets. However, the PRC's dominance of the global solar PV supply chain means that the UK's growing solar ambitions also necessarily entail a growing dependence on the PRC. As EU Commissioner Thierry Breton warned, there is a danger that Europe replaces dependence on Russian gas with dependence on the PRC's solar PV supply chain.[28] This threatens to undermine the very energy security and strategic autonomy that solar is meant to provide.

2.2 Strategic risks posed by reliance on the PRC's solar PV supply chain

The UK's ambitious plans to ramp up its solar capacity are entirely reliant on its ability to import solar modules – the final stage of the solar PV supply chain – 45.9% of which the UK imports directly from the PRC.[29] However, given the PRC's near total dominance at the upstream stages of the supply chain, this figure underplays the PRC's critical role. The next largest sources of the UK's solar module imports, the Netherlands (32.65%) and Germany (8.28%), rely heavily on the PRC inputs.[30] The Netherlands imports 27.8% of its unassembled cells from the PRC,[31] and Germany 83.3%.[32] Even for supply chains that mainly rely on non-PRC inputs, an increase or decrease in the PRC's supply are major determinants of the global market prices for polysilicon, wafers and other key components. As such, no solar PV supply chain is fully insulated from shocks in the PRC's production.

24 International Energy Agency, *Special Report on Solar PV Global Supply Chains*, 65; Johannes Bernreuter, 'Polysilicon Market – Free Info on Size, Shares, Trends & China', 8 July 2022, https://www.bernreuter.com/polysilicon/market-analysis/.
25 Department for Business, Energy & Industrial Strategy, 'Plans Unveiled to Decarbonise UK Power System by 2035', GOV.UK, 7 October 2021, https://www.gov.uk/government/news/plans-unveiled-to-decarbonise-uk-power-system-by-2035.
26 National Grid, 'How Much of the UK's Energy Is Renewable?', nationalgrid.com, 23 February 2023, https://www.nationalgrid.com/stories/energy-explained/how-much-uks-energy-renewable; Department for Energy Security & Net Zero, 'Powering Up Britain: Energy Security Plan' (Department for Energy Security & Net Zero, 4 April 2023), https://www.gov.uk/government/publications/powering-up-britain/powering-up-britain-energy-security-plan.
27 National Grid ESO, 'Future Energy Scenarios 2023', July 2023, Data Workbook-ES.05-08, https://www.nationalgrideso.com/document/283101/download.
28 Thierry Breton, 'Launch of the European Solar Photovoltaic Industry Alliance', Text, European Commission - European Commission, 9 December 2022, https://ec.europa.eu/commission/presscorner/detail/en/SPEECH_22_7619.
29 This includes Hong Kong.
30 HM Revenue & Customs. (2022). UK photovoltaic cell imports data, 2022 (HS Commodity Code: 854143). UK Trade Info. https://www.uktradeinfo.com/trade-data/ots-custom-table/ Accessed on 04/09/2023.
31 Centraal Bureau voor de Statistiek. (n.d.). Goods; border crossing, CN (38180010), countries. https://opendata.cbs.nl/statline/#/CBS/nl/dataset/85443NED/table?dl=9736B Accessed on 29 Sep 2023; Centraal Bureau voor de Statistiek. (n.d.). Goods; border crossing, CN (85414200), countries. https://opendata.cbs.nl/statline/#/CBS/nl/dataset/85441NED/table?dl=97368 Accessed on 29 Sep 2023.
32 Destatis Statistisches Bundesamt. (2022). German photovoltaic cell imports data, 2022 (HS Commodity Codes: 85414200 and 38180010). GENESIS - Statistisches Bundesamt. https://www-genesis.destatis.de/genesis/ Accessed on 28/09/2023.

The first challenge this presents is the risk of **supply chain disruption**. The solar PV supply chain is highly geographically concentrated, even beyond the country level. In 2021, 30% of the world's solar modules were produced in one PRC province, Jiangsu, with 14% of global production capacity of wafers located at a single PRC facility. The IEA and leading solar firms have warned that such concentration makes the solar PV supply chain highly vulnerable to shocks such as industrial accidents, natural disasters and pandemics.[33] A US government report outlines how a 2020 explosion at a plant operated by the PRC's GCL-Tech temporarily halted a tenth of the world's production capacity.[34] In total, technical issues at four major PRC polysilicon plants led to a 4% year-on-year decline in 2020 polysilicon production, which alongside the suspension of many PRC factories due to the COVID-19 pandemic, contributed to a near quadrupling of prices that year.[35]

The second challenge posed by the PRC's dominance is that of **supply chain weaponisation**. As renewable energy becomes a larger part of the global energy mix, the geopolitical leverage the PRC gains from controlling a critical component of that supply chain will only increase. The PRC has already shown a willingness to weaponise trade for strategic benefit: in July, the country implemented export controls on germanium and gallium products, two metals used in semiconductor manufacturing, in response to US-led export controls on chip-making equipment.[36] PRC exports of the products plunged, catching many firms off-guard and exposing a vulnerability in their critical raw material supply chain.[37]

The PRC government is already contemplating how best to exploit its strategic advantage in the solar PV supply chain. The PRC's Ministry of Commerce and Ministry of Science are currently considering including advanced solar wafer manufacturing equipment in export bans.[38] This would constrain the ability of other countries to develop alternative supply chains, increasing their dependence on imports of PRC solar. While there remains a strong trade incentive for the PRC to continue exporting to the West, this is diminishing as the PRC seeks to diversify its export markets through the Belt and Road Initiative. While the EU and the US still account for nearly half of the total value of the PRC solar exports, the PRC has actively redirected its solar panel exports to lower-income countries over the past five years.[39]

Increasing its ability to weaponise critical global supply chains is a stated long-term goal of the PRC government. The so-called 'dual circulation' strategy aims to increase self-sufficiency in critical supply chains while reducing reliance on exports to the West. This strengthens its hand in both imposing and responding to trade sanctions.[40] Earlier this year, Beijing passed a new Foreign Relations Law, designed to give more powers to respond to foreign sanctions, export controls and other measures that may be imposed upon it.[41] In such an event, it is likely that the PRC would seek to reduce the collateral damage of a sanctions package by targeting Western industries that rely heavily and asymmetrically on PRC inputs – such as the solar PV supply chain.

The most extreme scenario in which solar PV supply chains could both be disrupted and weaponised is conflict over the Taiwan Strait. The Taiwan Strait is the primary route for ships passing between East Asia and Europe, with almost half of the global container fleet and 88% of the world's largest ships by tonnage passing through the Taiwan Strait in 2022.[42] A PRC-imposed economic blockade or military action against Taiwan could wreak havoc on the global solar PV supply chain, causing extensive shipping delays and driving price increases. Such conflict would also see a major escalation in sanctions and counter-sanctions between G7 countries and the PRC – with an estimated US $3 trillion reduction in trade and financial flows.[43] In this context, the PRC government may choose to weaponise its dominance of the solar PV supply chain to counter foreign sanctions in other areas.[44]

However, as recent disputes have shown, even much less extreme scenarios could lead the PRC to take coercive economic action. Punitive trade sanctions imposed on Australia's agricultural and commodity exports in 2021 were triggered by Australia's call for an independent inquiry into the origins of COVID-19, while a wholesale ban on Lithuanian imports was triggered by the renaming of the Taiwan Representative Office in Vilnius. In an escalating dispute with the PRC, the UK's dependence on PRC solar constitutes a major vulnerability that threatens to undermine the UK's energy security.

33 International Energy Agency, *Special Report on Solar PV Global Supply Chains*, 58; Barney Jopson and Rachel Millard, 'Solar Supply Chains Must Diversify Away from China, Warns EDP', Financial Times, 25 September 2023, sec. Solar power, https://www.ft.com/content/6ecee5d2-e86b-49d3-9b7f-da937bf8b993.
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38 Murtaugh, 'China Mulls Protecting Solar Tech Dominance With Export Ban'.
39 Lili Pike, 'Following the Green BRICS Road', *China Dialogue* (blog), 1 September 2017, https://chinadialogue.net/en/business/10036-following-the-green-brics-road/.
40 World Integrated Trade Solution, 'China Electrical Apparatus; Photosensitive, Including Photovoltaic Cells, Whether or Not Assembled in Modules or Made up into Panels, Light Emitting Diodes Exports by Country | 2022 | Data', accessed 27 October 2023, https://wits.worldbank.org/trade/comtrade/en/country/CHN/year/2022/tradeflow/Exports/partner/ALL/product/854140#; Yingzhe Guo and Chang Liu, 'Unrestrained Investment Creates Looming Glut for China's Solar Supply Chain, Analysts Say - Caixin Global', 6 December 2022, https://www.caixinglobal.com/2022-12-06/unrestrained-investment-creates-looming-glut-for-chinas-solar-supply-chain-analysts-say-101975040.html.
41 Dennis Kwok, 'Xi's National Security Agenda: How Can Governments and Businesses de-Risk?', China Strategic Risks Institute (blog), 21 June 2023, https://www.csri.global/research/xis-national-security-agenda-how-can-governments-and-businesses-de-risk.
42 Kevin Varley, 'Taiwan Strait: Tensions Raise Risks in One of Busiest Shipping Lanes - Bloomberg', 2 August 2022, https://www.bloomberg.com/news/articles/2022-08-02/taiwan-tensions-raise-risks-in-one-of-busiest-shipping-lanes?leadSource=uverify%20wall.
43 Charlie Vest and Agatha Kratz, 'Sanctioning China in a Taiwan Crisis: Scenarios and Risks', *Atlantic Council* (blog), 21 June 2023, https://www.atlanticcouncil.org/in-depth-research-reports/report/sanctioning-china-in-a-taiwan-crisis-scenarios-and-risks/.
44 Lv and Patton, 'China Exported No Germanium, Gallium in August after Export Curbs'.

3. Modelling the costs of the UK's dependency

Modelling the economic impact arising from disruption to the UK's solar PV supply chain is a complex task that depends on a number of variables. Our model attempts to understand the cost in terms of the impact on household energy bills, the avenue by which ordinary UK citizens are most likely to feel a direct cost, in the event that the PRC blocks the export of solar goods to the UK.

Our model finds that a PRC export ban on polysilicon solar wafers – of which the PRC controls over 97% of world production capacity – could lead to the UK missing out on 20.4 GW of planned additions to solar capacity over a five-year disruption period. This scenario could then lead to a corresponding increase in energy bills of £4.30 billion by 2035, or £153 per household. This is due to the cost savings associated with solar, which is cheaper than other forms of energy and is projected to fall further in cost in the coming years.

A number of scenarios are also considered in our model. It is possible that the PRC chooses to impose weaker sanctions, with import bans at only the final solar modules stage of production. The UK's dependency here is lower (at 45.9%), so there would be a less extreme impact. This is likely to be an underestimate as the shock to global solar prices arising from PRC export bans could add further prohibitive costs to the UK's solar expansion. We also consider the costs associated with a minimum three-year disruption period, this being the average time it takes for a new polysilicon plant to come online. However, it is likely that it would take longer for production to scale up to replace the PRC's capacity, particularly for plants built in the US and Europe. Hence this model primarily considers a five-year time disruption period, which is a more realistic time frame for the global supply chain to recover.

Table 1 | Projected UK cumulative increased energy costs by 2035 in PRC solar export ban scenarios

		EXPORT BAN	
		Solar modules	**Solar wafers**
Disruption period	3 years	£1,483,901,889	£3,242,911,959
	5 years	£1,965,484,824	£4,295,360,959

Our methodology is only a first attempt at modelling a very complex problem with a number of intermediate scenarios and alternative contingencies. The results here are only meant to be indicative of the scale of the challenge posed by the UK's dependency on the PRC's solar PV supply chain. The PRC's ability to weaponise its solar PV supply chain could have real costs on ordinary citizens in the UK, reducing the UK's strategic autonomy and undermining its economic security.

4. Strategic priorities for securing the solar PV supply chain

The UK finds itself in a precarious position when it comes to securing the solar PV supply chain. Unlike the US and EU, the UK has no major solar manufacturing capacity to scale up. As such, the resilience of the UK's solar PV supply chain is highly dependent on the choices made by others – both the private companies which make up the UK's energy supply and the industrial policy of the US, EU and other partners. To meet this challenge, this paper recommends a three-pronged approach which encourages UK energy suppliers to de-risk supply chains, supports international efforts to diversify solar PV production and invests in the UK's leading-edge technology providers.

4.1 De-risking the UK's solar PV supply chain

The government must work with solar energy providers to ensure new installations are based on supply chains that are resilient and diverse and take into account the risks posed by the PRC's dominance over the solar PV supply chain. Despite being one of the first countries to privatise its energy market, the UK government still has some levers of influence to help energy companies avoid over-reliance on the PRC's solar PV supply chains as they ramp up solar generation capacity.

Setting minimum standards for supply chain resilience

The UK government has significant leverage over energy providers through the support it gives to the renewable energy industry, predominantly through the flagship Contracts for Difference Scheme. The Contracts for Difference scheme promotes investment in the UK's renewable power capacity by offering a guaranteed 'strike' price for solar and other forms of renewable electricity generation over a 15-year period. In the fifth round of the programme published in September 2023, support was given to 56 solar projects totalling 1.9 GW of solar power.[45]

Government support for Contracts for Difference should be made conditional upon providers demonstrating that their supply chains meet minimum standards for supply chain resilience. Criteria should be introduced at the bidding stage, and could include:

- **Supply chain diversity:** Bids should declare what proportion of the value of their supply chain originates from a single source. Mirroring the EU Critical Raw Materials Act and Net Zero Industry Act, the upper limit for such single source dependence could be set at 65% – with exceptions for a trusted group of allied countries.
- **Geopolitical risk assessment:** Bids should be assessed for their exposure to risks including trade sanctions and coercive economic diplomacy. In this respect not all sources of supply should be considered equal levels of risk. For example, supply chains based in a trusted group of countries such as the US, Europe or Japan may be considered at lower risk, while providers which are heavily reliant on the PRC may be considered at higher risk.
- **Contingency planning:** Bids should demonstrate their ability to continue their project plans in the face of adverse contingencies including supply chain disruptions and geopolitical fallout, such as using stockpiles or locating alternative sources of supply.

These criteria could be assessed as part of the Supply Chain Plan which large developers are already required to provide as part of the bidding process, though this currently focuses on the supply chain's impact on innovation and skills rather than its resilience. Once a contract has been awarded, a developer will be held accountable for the commitments they have made through the existing regular testing and penalty mechanisms.

If implemented, the UK would not be alone in establishing supply chain resilience criteria for government support. The EU's Net Zero Industry Act directs Member States to consider sustainability and resilience when awarding contracts or ranking bids for the deployment of net-zero technologies, with a particular focus on technologies for which the EU imports more than 65% of its supply – such as solar PV.[46]

Banning forced labour imports

Another avenue for de-risking the UK's solar PV supply chain is by raising ethical standards for solar PV imports. As noted above, the PRC's solar PV supply chain is deeply integrated with forced labour programmes in the XUAR and has

45 Andrea Mariano, 'UK Solar Contract for Difference (CfD) Allocation', *Pager Power* (blog), 16 October 2023, https://www.pagerpower.com/news/uk-solar-contract-for-difference-cfd-allocation/.
46 European Parliament, 'Net-Zero Industry Act | Legislative Train Schedule', *European Parliament*, accessed 3 November 2023, https://www.europarl.europa.eu/legislative-train/package-green-deal-industrial-plan-for-the-net-zero-age/file-net-zero-industry-act; ' Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on Establishing a Framework of Measures for Strengthening Europe's Net-Zero Technology Products Manufacturing Ecosystem (Net Zero Industry Act)' (2023), https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0161.

a significantly higher environmental impact than production elsewhere due to the high prevalence of coal in its energy mix. By raising these standards, the UK government can provide a strong demand side incentive for UK energy providers to explore alternative solar PV supply chains that have a lower carbon footprint and are less at risk of complicity in human rights abuses.

The UK's modern slavery legislation is ineffective and fast falling behind the standards set by other democratic countries. While the UK's Modern Slavery Act requires companies to publish a modern slavery statement outlining their efforts to remove forced labour from its supply chains, it provides no powers to penalise companies that fail to implement their plans. UK legislation is notably weaker than the new German Supply Chain Due Diligence Act, which penalises companies that fail to take adequate actions to avoid, prevent or remedy forced labour abuses in supply chains.[47] The UK's legislation should also be updated to mirror the proposed EU-wide ban on goods made with forced labour, which would see such goods forcibly removed from the EU market.[48] At the time of writing, the European Parliament is set to consider proposals to further strengthen this legislation by including additional requirements for companies with supply chains in areas at high risk of forced labour to demonstrate that their products are not complicit in modern slavery abuses.[49] By reversing the burden of proof from authorities to companies, these amendments serve to make the regulation far more effective by forcing companies to adopt a proactive and preventative approach.

4.2 Diversifying global solar production

Unlike the US and EU, the UK has few prospects for developing a domestic supply chain in solar. As such, it has a greater strategic interest in supporting initiatives to develop alternative solar PV supply chains outside of the PRC, and crucially, in gaining access to the end products. We describe this as a so-called 'friendshoring' strategy, whereby production that cannot be 'on-shored' is instead moved to friendly, allied third countries.

This section makes the case for a targeted approach to friendshoring which balances addressing strategic needs with commercial viability. Investing in the upstream stages of the solar PV supply chain (polysilicon, ingots and wafers) in Southeast Asian countries with low energy and capital costs (such as Vietnam and Malaysia) emerges as the best option on this calculus. By funnelling investment through initiatives such as the G7's Partnership for Global Infrastructure and Investment, 'friendshoring' can not only improve supply chain resilience but can also raise ESG standards and meet development needs.

While the UK will likely continue to import a substantial proportion of its solar PV from the PRC, building an effective 'friendshore' will increase the resilience of the supply chain as a whole and reduce the PRC government's ability to weaponise it. Alternative sites of production will give greater opportunities for scaling up production should the PRC's supply chains be suddenly cut off, allowing the supply chain to respond more quickly to geopolitical shocks.

Building an effective friendshore

In order to ensure best value for taxpayer money, government support for friend-shoring initiatives should take a targeted approach, taking into account both the strategic need and the commercial viability of a project.

There is a strong strategic case for prioritising friend-shore investments at the earlier stages of the solar PV supply chain. It is these stages at which the PRC's dominance is most pronounced, and at which the supply chain is most effectively weaponised – with the ability to put a stranglehold on all subsequent stages. The comparatively long lead time for new plants at the earlier stages of the supply chain also add to the strategic risk. While cell and module factories can be deployed in 6-12 months in most parts of the world, new polysilicon plants' lead time range from 30-40 months. On average, new plants in the US and Europe have the longest lead times across all stages of production, while those in the PRC and Southeast Asia can be built considerably quicker.[50]

In order to ensure commercial viability, 'friend-shoring' projects should be targeted at countries that have competitive capital and operational costs. According to IEA analysis, average investment costs per GW of solar production capacity are more than twice as expensive in the US and Europe compared to the PRC across all segments of the supply chain. In contrast, investment costs in Southeast Asian countries are much more cost competitive, being only 10-20% higher than the PRC at the polysilicon, and ingots and wafers stage, while investment costs in India at the modules stage are on par with the PRC's.[51] A capital investment of US$ 700 - 800 million could build a 10GW solar-grade polysilicon or wafers production facility in Southeast Asia of a comparable size to leading PRC plants.

47 José A. Campos Nave et al., 'The New German Supply Chain Due Diligence Act (LkSG) – What Needs to Be Done', 2 January 2023, https://www.roedl.com/insights/supply-chain-act-due-diligence-obligations.
48 Will Norman, 'EU to Ban Import and Export of Products Made with Forced Labour', PV Tech (blog), 17 October 2023, https://www.pv-tech.org/eu-to-ban-import-and-export-of-products-made-with-forced-labour/.
49 European Parliament, 'Towards an EU Ban on Products Made with Forced Labour | News | European Parliament', 16 October 2023, https://www.europarl.europa.eu/news/en/press-room/20231016IPR07307/towards-an-eu-ban-on-products-made-with-forced-labour; European Parliament Think Tank, 'Proposal for a Ban on Goods Made Using Forced Labour | Think Tank | European Parliament', accessed 8 November 2023, https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2023)739356; Paula Soler, 'MEPs Agree EU Ban on Forced-Labour Goods, but Council Stalls', EUobserver, 17 October 2023, https://euobserver.com/health-and-society/157566.
50 International Energy Agency, Special Report on Solar PV Global Supply Chains, 65.

To achieve commercially viable operating costs, the friendshore should be targeted at countries with low energy prices. Notably, Southeast Asian countries such as Vietnam and Malaysia, as well as Korea, and India, have energy costs comparable to the PRC. These countries already collectively account for 12% of global module production capacity, and so could benefit from vertical integration if new capacity could be built at the upstream stages of production. Although solar PV manufacturing in Latin America and Africa is still developing, the region has huge potential for developing greater manufacturing capacity with its cheap and clean energy and its burgeoning demand for solar PV as countries seek affordable ways to increase electricity output and consumption.

Table 2 | Solar PV manufacturing

Country	Average business electricity price (USD/kWh)[52]	Carbon intensity of electricity (g/kWh CO2)[53]	Existing PV-related manufacturing
P.R. China	$0.09	531.15	Polysilicon, wafers, cells and modules
EUROPE			
France	$0.24	257.38	Cells and modules [54]
Germany	$0.44	385.47	Polysilicon, cells and modules
LATIN AMERICA			
Argentina	$0.04	338.28	Limited existing manufacturing
Ecuador	$0.09	188.71	
ASIA			
Vietnam	$0.07	376.83	Wafers, cells, and modules[55]
Malaysia	$0.13	543.74	Polysilicon, wafers, cells, and modules[56]
AFRICA			
Ethiopia	$0.022	25.19	Modules[57]
Nigeria	$0.046	368.22	Polysilicon, ingots, wafers, cells, and modules (under development)[58]
Kenya	$0.149	100.57	Modules[59]

Finally, building an effective friendshore will require investing in projects which have a realistic chance of competing with the advantages that have allowed PRC firms to dominate the global market. Most significantly, viable projects must be able to raise enough capital investment to achieve the economies of scale utilised by leading PRC firms. While there is no precise scale threshold for an individual plant to achieve, analysts have found that leading firms typically have 3 to 5 GW capacity plants at the downstream cell and module level, and around 10 GW at the upstream polysilicon, ingot and wafer level.[60]

51 International Energy Agency, 87.
52 GlobalPetrolPrices.com, 'Electricity Prices around the World - Mar 2023', GlobalPetrolPrices.com, accessed 7 November 2023, https://www.globalpetrolprices.com/electricity_prices/.
53 Our World in Data, Ember, and Energy Institute Statistical Review of World Energy, 'Carbon Intensity of Electricity', Our World in Data, accessed 7 November 2023, https://ourworldindata.org/grapher/carbon-intensity-electricity?tab=table.
54 Will Norman, 'PV Startup Carbon Selects Location for Planned 5GW/3.5GW Cell and Module Factory in France', PV Tech, 7 March 2023, https://www.pv-tech.org/pv-startup-carbon-selects-location-for-planned-5gw-3-5gw-cell-and-module-gigafactory-in-france/.
55 Willie Jiang, 'Top 12 Solar Manufacturers in Vietnam 2022', *SolarFeeds Magazine* (blog), 26 June 2023, https://www.solarfeeds.com/mag/top-solar-manufacturers-in-vietnam/.
56 Adam Aziz and Jia Teng Liew, 'Cover Story: US Tariffs Shine Spotlight on Malaysian Solar Panel Industry', *The Edge Malaysia*, 8 June 2023, https://theedgemalaysia.com/node/669102; Solar Magazine, 'Malaysia Solar Energy Profile', Solar Magazine, accessed 7 November 2023, https://solarmagazine.com/solar-profiles/malaysia/;
E. Borensztein, J. De Gregorio, and J-W. Lee, 'How Does Foreign Direct Investment Affect Economic Growth?', *Journal of International Economics 45*, no. 1 (June 1998): 115–35, https://doi.org/10.1016/S0022-1996(97)00033-0.
57 Ethiopian News Agency, 'Precise Consult to Assemble, Manufacture 250,000 Solar Home Systems in Ethiopia', *ENA English*, accessed 7 November 2023, https://www.ena.et/web/eng/w/en_37900.
58 Jonathan Touriño Jacobo, 'Nigeria Breaks Ground on US$171 Million Solar Cell Production Plant', PV Tech, 28 March 2023, https://www.pv-tech.org/nigeria-breaks-ground-on-us171-million-solar-cell-production-plant/;
Uchechukwu Okoro, 'Nigerian PV Panel Production Gets Going at New Lagos Plant', *Energy & Utilities*, 24 October 2023, https://energy-utilities.com/nigerian-pv-panel-production-gets-going-at-new-news122767.html.
59 Dinfin Mulupi, 'Manufacturing Solar Panels in East Africa: Rising Demand, but Challenges Remain', How we made it in Africa, 28 March 2016, https://www.howwemadeitinafrica.com/manufacturing-solar-panels-east-africa-rising-demand-challenges-remain/53859/;
Penninah Munyaka and Anna-Lena Becker, 'Solar Power, the next Frontier for Kenya's Renewable Energy...', *Rödl & Partner* (blog), accessed 7 November 2023, https://www.roedl.com/insights/renewable-energy/2016-07/solar-power-frontier-kenya-renewable-energy-sector.
60 Alberto Bettoli et al., 'Rebuilding Europe's Solar Supply Chain' (McKinsey, 13 December 2022), https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/building-a-competitive-solar-pv-supply-chain-in-europe.

Industry trends point towards ever larger scales of production, with 20 to 40+ GW capacity at the ingot and wafer stage and 10 to 30 GW at the cells and modules becoming increasingly common.

Forums for financing the friendshore

The UK is part of two existing initiatives which could play an important part in supporting friend-shoring initiatives in the solar PV supply chain. These are the G7's Partnership for Global Infrastructure and Investment, launched in 2021, and the Minerals Security Partnership, which met for the first time this year.

The Partnership for Global Infrastructure and Investment (PGII), previously known as the Build Back Better World (B3W) initiative, aims to provide an alternative to the PRC's Belt and Road Initiative (BRI) for infrastructure development in low- and middle-income countries. The partnership is led by the G7 democracies and seeks to mobilise US $40+ trillion of private-sector capital to address the infrastructure need in the developing world, including in the area of climate change mitigation and adaptation. Leaders from Canada, France, Germany, Japan, Italy, the United Kingdom, the United States, and the EU have so far aimed to mobilise a total of US $600 billion for PGII in public and private financing.[61]

Dedicating even a small proportion of this budget could make a significant impact on the solar PV supply chain if invested in Vietnam, Malaysia or other countries with low capital and operational costs. The IEA estimates that the minimum investment required for new polysilicon capacity in Southeast Asia is approximately US$ 80 million/GW, and US$ 70 million/GW for solar wafers.[62] This means that a US $3.2 billion and US $1.75 billion investment in Southeast Asia could build 40GW of polysilicon production and 25GW of wafer production capacity, respectively, equivalent to over 10% of global production in 2022. Together these initiatives would total to just under US $5 billion – less than 1% of the PGII finance target.

Using PGII funds to funnel investments into building solar production capacity in low- and middle-income countries could also meet important development goals. As highlighted above, countries in Southeast Asia, Latin America and Africa could all be viable sites for upstream solar production. By channelling investments into these areas, the PGII can stimulate local economies, creating approximately 1,300 manufacturing jobs per gigawatt of solar production capacity.[63] Funding through the PGII is envisioned to be contingent upon adherence to high environmental and labour standards. This approach not only elevates the ethical framework within which infrastructure projects operate but also addresses concerns over the solar PV supply chain link to forced labour abuses in the XUAR.

Minerals Security Partnership (MSP)

The UK hosted the first meeting of the Minerals Security Partnership (MSP) in October this year, bringing together 14 countries representing over 50% of world GDP.[64] The MSP aims to catalyse public and private investment in critical minerals projects across extraction, processing and recycling. While not formally stated, the PRC's non-participation suggests that diversification of supply chains away from the PRC's dominance is a core objective of the partnership. Additionally, the UK has signed bilateral statements of intent on critical minerals with Japan and Australia.[65]

So far, the MSP has announced a number of projects across mineral extraction, processing and recycling. Two projects include copper, which accounts for 5-12% of the value-based material composition of silicon-based panels, with the PRC producing 42% of the world's copper supply.[66] Future MSP initiatives could also focus on zinc, which is listed by the US and the EU on their respective critical materials lists.[67] Zinc has applications in both the solar and wind industry, and has gallium and germanium as byproducts – two minor metals needed for semiconductor manufacturing of which the PRC dominates world production.[68]

61 The White House, 'FACT SHEET: President Biden and G7 Leaders Launch Build Back Better World (B3W) Partnership', *The White House* (blog), 12 June 2021, https://www.whitehouse.gov/briefing-room/statements-releases/2021/06/12/fact-sheet-president-biden-and-g7-leaders-launch-build-back-better-world-b3w-partnership/;
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62 International Energy Agency, *Special Report on Solar PV Global Supply Chains*, 22, 24, 86.
63 International Energy Agency, 94.
64 Department for Business and Trade and Nusrat Ghani, 'UK to Host Minerals Security Partnership for First Time to Boost Investment in Critical Minerals', *GOV.UK*, 11 October 2023, https://www.gov.uk/government/news/uk-to-host-minerals-security-partnership-for-first-time-to-boost-investment-in-critical-minerals.
65 Department of Industry, Secience and Resource, 'Joint Statement of Intent between Australia and the United Kingdom on Collaboration on Critical Minerals', Partnership or agreement, 4 April 2023, https://www.industry.gov.au/publications/joint-statement-intent-between-australia-and-united-kingdom-collaboration-critical-minerals;
Rishi Sunak and Fumio Kishida, 'THE HIROSHIMA ACCORD: AN ENHANCED UK-JAPAN GLOBAL STRATEGIC PARTNERSHIP', accessed 27 October 2023, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1157778/The_Hiroshima_Accord.pdf.
66 International Energy Agency, *Special Report on Solar PV Global Supply Chains*, 21; U.S. Geological Survey, 'Copper', Mineral Commodity Summaries, *U.S. Geological Survey*, January 2023, https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-copper.pdf.
67 European Commission, 'Critical Raw Materials', accessed 27 October 2023, https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en;
'U.S. Geological Survey Releases 2022 List of Critical Minerals | U.S. Geological Survey', 22 February 2022, https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals.
68 Natalie Liu, 'Tennessee Refinery Could Break Chinese Chokehold on Two Critical Minerals', VOA, 15 August 2023, https://www.voanews.com/a/tennessee-refinery-could-break-chinese-chokehold-on-two-critical-minerals/7226979.html.

4.3 Investing in leading-edge technologies

While the PRC government has supported its firms to become world leaders in crystalline silicon-based solar PV, a number of the PRC and non-PRC firms are competing in the development of leading-edge, higher efficiency solar panels. Most notably, perovskite solar cells (PSCs) have emerged as a promising alternative to traditional crystalline silicon panels. UK universities and firms could play an important role in the research and development of PSC technologies.

Perovskites solar cells

The term 'perovskite' refers not to a specific material, like silicon, but rather to a whole family of compounds.[69] There are different types of PSCs, including thin-film PSCs and hybrid or 'tandem' PSCs which combine perovskites with silicon. Recent innovations have seen PSCs competing with and even surpassing the efficiency of traditional solar cells. The current efficiency record for traditional silicon-only solar cells is 24.5% in commercial cells and 27% in the laboratory. Thin-film PSCs have come close to matching this level of efficiency, at around 24%, while tandem cells have passed the 30% efficiency milestone.[70]

One advantage of PSCs is the relatively lighter demand for raw materials compared to crystalline silicon panels. Thin-film PSCs eliminates the need for polysilicon, which decreases supply chain vulnerabilities stemming from tension with the PRC. While tandem solar cells do combine polysilicon with perovskites, the efficiency gains in the final product serve to reduce the overall level of reliance on polysilicon supply chains compared to traditional silicon-only solar panels. Further advantages over traditional silicon-only solar panels include a less energy-intensive manufacturing process, which could contribute to lower production costs and a lower environmental footprint.

However, there are still factors limiting the widespread commercialization of PSCs. One significant challenge in adopting PSCs has been their longevity, as they tend to degrade faster than crystalline silicon panels.[71] Further research into increasing the durability of PSCs and lowering production costs are crucial to their commercial viability.

Supporting the UK's leading edge in PSCs

The UK is a world leader in the development of PSC technologies. Oxford PV, a private company spinout from the University of Oxford, has set world records for the efficiency of their tandem cells and is expected to be the first company to sell these next-generation solar cells to the public.[72] While the firm does not plan to have a manufacturing capacity in the UK, it has maintained its R&D centre in Oxford since 2017. Additionally, several UK universities are undertaking research into making PSCs commercially viable, including increasing efficiency, durability and novel applications.

Leveraging investment into PSC research will be critical to the UK maintaining its leading edge. The UK Research and Innovation Fund and its Innovate UK programme, have already supported a number of PSC R&D programmes and should be further expanded. With US solar firms benefiting from large amounts of financial support under the US Inflation Reduction Act, and the EU considering various initiatives to support its solar PV supply chain, the UK risks falling behind its peers unless it can direct greater investment into R&D.

The UK's leading edge in PSC development can play an important role in its efforts to build a resilient 'friend-shore' in solar. The UK has already committed to a renewable energy partnership with Japan, with cooperation on PSCs named as a key focus of the agreement.[73] Japan already has established expertise in PSC development and is also one of the world's top producers of iodine, a component necessary to stabilise PSCs.[74] This is an encouraging first step and should be expedited to see the commercialisation and manufacture of PSC technologies.

The UK could seek to develop similar cooperative arrangements with the EU, where scaled-up supply chains would feed back into the UK market. Of particular relevance is the EU's Solar PV Alliance – a network which seeks to link solar manufacturers with potential investors. While currently restricted to firms belonging to EU member states, there is a strong argument for including UK firms on the basis that UK advances in PSC R&D will likely lead to increased manufacturing through the EU's supply chains. The tariff-free trade between the UK and EU on solar PV means that there is a mutual benefit to making advances in solar technology, wherever the manufacturing takes place.

69 David L. Chandler, 'Explained: Why Perovskites Could Take Solar Cells to New Heights', *MIT News | Massachusetts Institute of Technology* (blog), 15 July 2022, https://news.mit.edu/2022/perovskites-solar-cells-explained-0715.
70 Innovation News Network, 'New Perovskite Solar Cells Smash Power Conversion Efficiency Record', *Innovation News Network* (blog), 23 June 2023, https://www.innovationnewsnetwork.com/new-perovskite-solar-cells-smash-power-conversion-efficiency-record/34113/;
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71 Power Electronics Insider, 'New Perovskite Solar Cell Has a Commercially Viable Lifetime', *Tech Briefs*, 9 September 2022, https://www.techbriefs.com/component/content/article/tb/insiders/pe/stories/46585.
72 'Revolutionising Solar Power Technology: Oxford PV | University of Oxford', accessed 27 October 2023, https://www.ox.ac.uk/research/research-impact/revolutionising-solar-power-technology-oxford-pv.
73 Department of Industry, Secience and Resource, 'Joint Statement of Intent between Australia and the United Kingdom on Collaboration on Critical Minerals'.
74 Walter James, 'Perovskite: Japan's Hope?', 2 September 2023, https://www.linkedin.com/pulse/perovskite-japans-hope-walter-james;
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Table 3 | UK universities working on perovskite solar cells

University	Project Description
University of Warwick	Investigations into the use of PSCs in space and efficiency improvements.[75]
Swansea University	Developing large-scale manufacturing techniques of PSCs.[76]
Queen Mary University of London	Manufacturing techniques to make more efficient and stable PSCs.[77]
University of Cambridge	Improving PSC efficiency.[78]
University College London (UCL)	PSC design and commercial viability.[79]
Teesside University and University of Leicester	Lowering lead content in PSCs and increasing efficiency.[80]
University of Manchester	Lowering lead leakage in PSCs and increasing efficiency.[81]

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76 Swansea University, 'Swansea University Academics Develop World's First Completely Roll-to-Roll Printable Perovskite Solar Cell', *Swansea University*, 15 March 2023, https://www.swansea.ac.uk/press-office/news-events/news/2023/03/swansea-university-academics-develop-worlds-first-completely-roll-to-roll-printable-perovskite-solar-cell.php.
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81 'Research Helps Solar Technology Become More Affordable', Research helps solar technology become more affordable, 17 February 2021, https://www.manchester.ac.uk/discover/news/research-helps-solar-technology-become-more-affordable/.
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5. Policy recommendations

In 2023, the UK government launched its Solar Taskforce, which aims to coordinate key players to meet the solar deployment ambition of 70 GW by 2035 and is set to release a report in 2024. It is working on a strategic roadmap, focusing on reducing installation costs, improving grid access, and boosting UK skills and jobs. The Taskforce is also identifying opportunities to secure resilient supply chains within the global market, helping UK businesses to export their expertise.

In line with the aims of the Solar Taskforce, our policy recommendations take a bold and comprehensive approach to securing the UK's solar PV supply chain based on the strategic priorities set out in the previous section.

1. De-risking the UK's solar PV supply chain

→ **Incorporating resilience criteria into the Contracts for Difference scheme:** Government support for energy providers through Contracts for Difference should be conditional upon providers meeting minimum requirements for supply chain resilience. We suggest that this includes criteria on supply chain diversity (which if modelled on the EU's Critical Raw Materials Act, caps dependence on one country at 65%, with exceptions for a trusted group of low risk countries), a geopolitical risk assessment and contingency plans for supply chain disruption. Such criteria could be incorporated within the Supply Chain Plan or other stages of the bid and monitored through the ongoing testing process.

→ **Strengthening modern slavery legislation:** Raising ethical standards will help build a more diverse and resilient solar PV supply chain. Penalising companies which fail to take adequate actions to avoid, prevent or remedy forced labour abuses would be a necessary first step. The UK should also seek to emulate proposed EU legislation banning forced labour goods from entering the UK market, with more stringent requirements for imports from areas at high risk of forced labour.

2. Diversifying global solar PV production

→ **Investing in viable, large-scale, upstream solar production:** The UK should work with its allies through initiatives such as the G7's Partnership for Global Infrastructure and Investment to raise public and private finance for new solar production facilities in low and middle-income countries. In order to be commercially viable, capital investment must be sufficiently high to achieve economies of scale, and take place in countries with competitive energy costs. Such funding would be most effectively targeted at the strategically vulnerable polysilicon, ingots and wafers stage of the supply chain, with Vietnam and Malaysia emerging as attractive candidates. An investment of US $5 billion – less than 1% of the PGII finance target – could build up to 40 GW of polysilicon production and 25 GW of wafer production capacity.

→ **Expanding the Minerals Security Partnership (MSP):** The MSP presents a positive opportunity to reduce dependency on the PRC's critical mineral supply chains. Future MSP initiatives should build capacity in copper and zinc, both of which have important applications in the solar PV supply chain. Zinc's by-products, gallium and germanium, also have applications in semiconductor manufacturing.

3. Investing in leading-edge technologies

→ **Leveraging investment into perovskite solar cells (PSCs):** The UK conducts world-leading research in PSCs but desperately needs more funding if it is to compete with increased US and EU funding for green technology development. The UK Research and Innovation Fund and its Innovate UK programme should identify and fund projects that will help British firms conduct further research and development into the commercialization of PSCs.

→ **Fostering UK-EU collaborations on PSCs:** The UK should lobby for UK solar firms to be included within the EU's Solar PV Alliance. This would boost investment in UK firms conducting research and development into PSCs, which could then also benefit European countries where PSC manufacturing could take place. Cooperation could boost the resilience of the solar PV supply chain for both the UK and EU and could be complementary to the announced UK-Japan Renewable Energy Partnership.

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Methodology annexe

Methodology

Our model aims to project:

A) The impact of PRC export bans on the UK's ability to install new solar capacity in a particular year;

B) The corresponding additional cost of electricity generate via other sources compared to generating the same amount via solar over that year; and

C) The corresponding cumulative impact over a three or five year period, and totalled on the national level or divided per household.

To calculate A), our model multiplies the UK's dependence on PRC (including Hong Kong) imports for the solar product subject to export ban (modules or polysilicon wafers) by the government targets for new solar capacity installation in that year.

E.g. 45.9% * 4.21GW = 1.93 GW of missing new solar capacity installations.

To calculate B), our model multiplies the amount of missing new solar capacity installation by the 'load factor' (i.e. the projected average efficiency per GW of solar installation per hour) by the number of hours in a year to to calculate the amount of electricity that will have to be generated by other sources, which is then multiplied by the difference between government projections of wholesale energy prices for that year and government projections for solar energy prices for that year.

E.g. 1.93 GW * 11% load factor * 8760 hours * (£104300/GWh-£41000/GWh) = £117.7 million additional cost

To calculate C), the figures for B) of each year are summed over the specific three or five year time period and up to 2035. The cost is added together to create a total UK cost by 2035, or divided by the number of households in the UK to create a per household cost.

Figures used and sources

Table 4 | Outlook

Variable	Description	Data source
Solar Capacity Needed by 2035	The UK government sets a target of 70 GW in total for solar energy by 2035. With 15.2 GW installed by June 2022, the UK needs to install 4.21 GW of solar capacity per year from.	UK targets from "Powering Up Britain" (2023)[84] UK total solar capacity (2023)[85]
Dependence on the PRC	Scenario 1: "Weak Sanctions" – 45.9% of the UK's 2022 imports of photovoltaic cells were from the PRC (including Hong Kong)	HMRC exports data[86]
	Scenario 2: "Strong Sanctions" – the PRC controls 96.8% of polysilicon wafer manufacturing worldwide	IEA[87]
Projected Price Difference	Wholesale baseload energy price projections, Solar cost projections (2025: £41/MWh, 2030: £37/MWh, 2035: £30/MWh)	Government Projections (Oct 2023)[88] and Levelised Cost Estimates[89]
Solar PV Load Factor	Constant 11%	Government Estimates[90]
Population	Constant at 67.0 million (2021) or 28.1 million households	ONS 2021 figure for population size[91] ONS 2023 figure for number of households[92]

Assumptions

Here is a breakdown of our key assumptions and the reasons behind them:

→ **Rate of new solar capacity installations:** We assume the UK will install solar capacity at a constant rate each year in order to reach its 2035 targets (an additional 4.21 GW each year between 2022 and 2035).

→ **Impact of sanctions:** We assume that the impact on the UK's solar PV installation rate during the disruption period will be of equal proportion to the dependence on the PRC for the product on which sanctions are imposed (i.e. a 45.9% decrease for 'weak' export bans on solar modules, or a 96.8% decrease for 'strong' export bans on polysilicon wafers). We believe this is a conservative estimate as it assumes that non-PRC supply is not disrupted, when in reality the affordability and availability of non-PRC supply would likely decrease significantly in response to this shock.

→ **End of disruption period:** We assume that the UK's solar PV installations after the disruption period has ended will return to the 4.21 GW annual new capacity rate in line with the original 2035 targets. This could be an overestimate if solar PV prices never fall back to normal, thereby prohibiting installation at the previously planned rate. This could be an underestimate if energy providers decide to install at a higher rate to fill the gaps in their missing solar capacity.

→ **Beginning of disruption period:** Our model calculates on the basis that the 3 or 5 year disruption period will begin in 2024. Moving the beginning of the disruption period to other years would give different results due to the changing costs of both solar electricity generation and wholesale electricity generation.

→ **Projected Price Difference:** We rely on government projections for both wholesale energy prices and the cost of solar energy. We acknowledge that disruptions might influence broader energy prices but do not model such disruptions.

→ **Solar PV Load Factor:** We use a constant load factor of 11%, in line with government estimates for solar PV.

→ **Population:** We maintain a constant population size of 67.0 million (2021) or 28.1 million households, recognizing that these assumptions could overstate per household impacts due to expected population growth.

The following table summarises the impact of disruptions:

83 Margaret Major, 'Solar Taskforce Drives Forward on Grid Access, Supply Chain, Skills and the Rooftop Market - Renewable Energy Installer & Specifier', *Renewable Energy Installer & Specifier*, 11 July 2023, https://www.renewableenergyinstaller.co.uk/2023/07/solar-taskforce-drives-forward-on-grid-access-supply-chain-skills-and-the-rooftop-
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87 International Energy Agency, *Special Report on Solar PV Global Supply Chains*.
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89 Department for Energy Security & Net Zero, 'Electricity Generation Costs 2023', October 2023, 31.
90 Department for Energy Security & Net Zero, 'Electricity Generation Costs 2023'.
91 Office for National Statistics, 'Population Estimates for the UK, England, Wales, Scotland and Northern Ireland - Office for National Statistics', 21 December 2022, https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/bulletins/annualmidyearpopulationestimates/mid2021.
92 Office for National Statistics, 'Families and Households in the UK 2022', 18 May 2023, https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/bulletins/familiesandhouseholds/2022.

Table 5 | The Impact of Disruptions

	OUTPUT			
DURATION	**3 years**		**5 years**	
	Weak sanctions	**Strong sanctions**	**Weak sanctions**	**Strong sanctions**
How many GW of planned installation solar capacity would be missed? (GW)	5.804584615	12.24021231	9.674307692	20.40035385
Average price difference between wholesale energy price and solar energy (GBP/MWh)	£53	£53	£63	£63
National cumulative loss after three years (2027) (GBP)	£896,232,740	£1,958,622,664		
Per household cumulative loss after three years (2027) (GBP)	£32	£69		
Per capita cumulative loss after three years (2027) (GBP)	£13	£29		
National cumulative loss after five years years (2029) (GBP)			£1,237,423,902	£2,704,260,167
Per household cumulative loss after five years (2029) (GBP)			£44	£96
Per capita cumulative loss after five years (2029) (GBP)			£18	£40
National cumulative loss by 2035 (GBP)	£1,519,326,108	£3,320,327,874	£2,000,909,043	£4,372,776,874
Per household cumulative loss by 2035 (GBP)	£54	£118	£71	£155
Per capita cumulative loss by 2035 (GBP)	£23	£50	£30	£65

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