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Published in:
Energy Research & Social Science

DOI:
10.1016/j.erss.2023.103256

2023

Document Version:
Publisher's PDF, also known as Version of record

Energy Research & Social Science 104 (2023) 103256

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

Turning the tanker? Exploring the preconditions for change in the global petrochemical industry

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A R T I C L E I N F O

Keywords:
Petrochemical industry
Sustainability transitions
Transition tensions
Climate policy
Fossil fuel lock-in
Industry renewal

A B S T R A C T

Meeting the goals set out in the Paris Agreement will require rapid and deep reductions of greenhouse gas emissions (GHG) across all sectors of the global economy. Like all major societal transformations, this climate transition will impact both social and technical aspects of society and, depending on how it evolves, will reallocate social and economic benefits and costs differently. Recognising the importance of decarbonising key industry sectors with large GHG emissions and an significant impact on society, this study explores the opportunities and tensions involved in a transition of the petrochemical industry. We do so by analysing how access to natural resources, the petrochemical industry's role in the economy and the socio-political landscape in key petrochemical producing countries impacts prerequisites for change. The assessment shows that devising adequate policy responses, building legitimacy for change and potentially building bottom-up pressure for a timely climate transition are likely to look very different in the 10 countries with the greatest active petrochemical capacity in the world: China, the United States, India, South Korea, Saudi Arabia, Japan, Russia, Iran, Germany and Taiwan. The indicators used to explore the prerequisites for change all point to areas where actions and policies must advance for a transition to be realised. This includes efforts to cap fossil feedstock supply and production capacity, efforts to limit and ultimately reduce demand for plastics and fertilisers, and measures to formulate transition strategies and policies that capture and provide agency for communities and groups that are currently on the receiving end of negative health and environmental impacts from the petrochemical industry and that will also, in many cases, be most closely affected by a transition.

1. Introduction

The message from the IPCC:s 6th assessment report [1] is clear: 'any further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all'. Despite this, a great deal of evidence indicates that global greenhouse gas emissions (GHG) have yet to peak. By the end of 2021, global GHG emissions were back to pre-pandemic levels. This bounce-back was driven by growth in coal use in the power and industry sectors in China but also by a return to 'normal' fossil-intensive economic activities across the globe [2,3]. A steady cost decline for renewable power generation technologies [4], continuous improvements in the performance of energy storage, and the parallel and rapid development in electric mobility give reason for optimism about the chances of phasing out fossil fuels from the electricity and transport sectors in the relative near term [5]. However, as traditional demands for oil – and for vehicle fuels in particular – are set to decline, and as demand for products such as plastics continues to rise, chemical manufacturing has increasingly become an attractive option for oil and gas companies and fossil fuel exporting countries to make up for losses in other markets [6]. Investments in production capacity and infrastructure in the petrochemical industry have increased significantly in the last decade, and unabated this trend is projected to continue well into the 21st century [7]. Recent analysis suggests that petrochemical manufacturing will be the largest source of growth for oil use by mid-century [7]. As the petrochemical industry contributes significantly to global GHG emissions, both through direct emissions from the production of basic chemicals in the form of methanol, ammonia and high-value chemicals (ethylene, propylene, benzene, toluene, xylenes) and, with varying degrees of delay, through the combustion (plastics) and use (fertilisers) of end-use products [8], this trend is incompatible with the goals set out in the Paris Agreement. In parallel, the ever-increasing

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https://doi.org/10.1016/j.erss.2023.103256
Received 23 February 2023; Received in revised form 12 July 2023; Accepted 17 August 2023
Available online 26 August 2023

demand for plastics, fertilisers and other end-use products means that the petrochemical industry is also at the centre of concerns around toxicity and solid waste pollution [9,10]. Thus, while much attention has been directed towards measures to reduce emissions from the primary production of basic chemicals [11,12], radically reducing the climate impact from the petrochemical sector while simultaneously addressing these wider environmental challenges will require strong measures to reduce, reuse and recycle chemical end-use products in general and plastics in particular [13]. The focus of this study is on the petrochemical industry (including coal-based chemical production), the largest contributor to the overall feedstock demand in the chemical industry [7,14] and the wider socio-technical challenges [12] involved in the transition away from fossil-based carbon in the industry.

In the face of current trends, curbing and radically reducing the climate impact from the petrochemical sector will be a monumental challenge. Mah [15] describes how escaping the current petrochemical lock-in poses a multiscale problem related to the continued reliance on (both essential and seemingly superfluous) chemically derived products, not the least in the Global South; a rising demand for plastics in green technologies; the limited availability of low carbon energy and alternative feedstock; and local dependencies where cities and communities around the world have developed around economies that are dependent on petrochemical production.

Handling this multiscale challenge will require multiscale responses, including efforts at the global and national level to halt new and scale back existing fossil fuel production capacity, scale up alternative production, limit overall demand and improve circularity. The power to break the current fossil lock-in of the petrochemical industry largely lies in a relatively limited number of corporate boardrooms [16–18], and the willingness and ability of policymakers to build pressure will obviously be key to reversing the current trend. However, to build legitimacy, prevent the overriding of local democracy and handle the conflicts of interest that are an inevitable part of large-scale socio-technical change, the top-down driven climate transition must also be complemented with processes that capture and provide agency for communities and groups on the frontlines of the transition [19–21]. The 'just transition' framework – which is based on the idea that justice and equity must form an integral part of the transition towards a low-carbon world – has increasingly become a common denominator in efforts to bring attention to and mobilise around these wider socio-economic dimensions of sustainability transition [22]. Although the concept of a just transition has gained traction in both the academic and wider political debate, the socio-economic interactions of fossil-fuel-intensive industries in specific communities are not well studied or understood [23]. Bazilian et al. [23] argue that, in order to be politically and socially sustainable (or even feasible), policies aimed at phasing out or transforming the legacy fossil industry must acknowledge the potentially disruptive effects on individuals and communities.

The aim of this article is to explore the prerequisites for change in the global petrochemical industry. This study combines an overview of global and regional trends in the petrochemical industry with a more in-depth mapping and exploration of the prerequisites for escaping the current fossil lock-in within the petrochemical industry, with a focus on the 10 countries that are currently home to more than 70 % of the operational petrochemical capacity. Our assessment of country-level contexts and prerequisites is based on a set of three main categories of indicators that describe the context in terms of the availability of natural resources, the petrochemical industry's role in the economy, and the socio-political landscape. The study is an attempt to explore the space left between the typically more top-down techno-economically oriented studies investigating pathways for transitioning the chemical industry (see e.g. Ref. [8]) and the more in-depth case studies focusing on regions and communities with deep – and often complex – relations to the industry (see e.g. Ref. [20]).

The rest of the article is structured as follows. In Section 2, we set the scene by providing a brief review of the literature on pathways for climate transition in the petrochemical industry and Just Transitions, which provides a basis for the selection of indicators explored in this study. In Section 3, we describe the scope and method of this study. In Section 4, we present our findings. Finally, in Section 5, we conclude and outline key areas for further investigation and for policy action.

2. Theoretical points of departure

In this section, we first provide a brief overview of the literature exploring different possible pathways that can lead to a climate transition in the petrochemical industry. Thereafter, we review lessons from the wider sustainability transitions literature, with a particular focus on the concept of a 'just transition' and its relevance to this work. Finally, we motivate our scoping and the selection of indicators used in the later assessment.

2.1. Potential pathways for climate transition in the petrochemical industry

Several reports and scientific articles use scenario modelling to investigate pathways to decarbonise the petrochemical industry, including both studies that encompass all industrial sectors [24,25] and studies that focus on the petrochemical industry [26–31]. Most of these scenarios envision some forms of technologically focused solutions for decarbonisation, including carbon capture and storage (CCS), carbon capture and utilisation (CCU), green hydrogen, plastics recycling and bio-based feedstocks, while maintaining or increasing petrochemical production levels. While many of these scenarios achieve GHG emission reductions that align with the goals of the Paris Agreement, all require substantial resources. For instance, the ambitious scenario in a study by DECHEMA [28] – which achieves an 84 % emissions reduction compared with the business-as-usual scenario – requires a fourth of the sustainably available non-food biomass and more than half of all low-carbon power (renewables, nuclear, and fossil CCS) assumed to be globally available by the IEA in 2015 [32]. Similarly, Galán-Martín et al. [31] find that the renewable carbon routes with the largest GHG emissions reductions exceed Earth's biodiversity boundary by 30 %. Looking at a scenario in which all EU plastics would be produced with electricity and CCU, Palm et al. [33] estimate that 1400–1900 TWh of electricity would be required for this scenario in 2050, which can be compared with the 1100 TWh of renewable electricity production in the EU today (Ember, 2022). Similarly, Kätelhön et al. [29] show that a reliance on CCU for decarbonisation would require 55 % of projected global electricity production in 2030. Thus, a transformation to a net-zero chemical and petrochemical industry will require a mixed portfolio of solutions that combine net-zero routes (including e.g. energy efficiency, renewables-based process heating, biomass feedstocks, synthetic hydrocarbons from green hydrogen and CO_2, and CCS) with circularity and demand-side measures [30,34].

In an effort to broaden the vision of what decarbonisation of the petrochemical industry may look like, Bulkeley et al. [35] expand on the above-mentioned technologically focused pathways by describing typical visions assumed by different groups, including social movements and scientific advisory boards. Similarly, Bauer et al. [36] describe and assess the feasibility of archetypal transition pathways that span across four industries – including the petrochemical industry – moving beyond the focus on early stages of value chains.

Five overall transition pathways, outlined in Table 1, stand out in the literature: the fossil capture, green hydrogen, bio, circularity and less-is-more pathways. The viability of each production route or combination of production routes in a specific location will be linked to the availability of energy and natural resources [34].

2.2. Theory on a just transition

Societal transitions – such as the substantial transformation of the

Table 1
Overview of pathways for transition in the petrochemical industry, including key measures and key resources. These pathways are not all-encompassing but capture the (most) commonly portrayed technological and behavioural directions of change, beyond general efficiency and optimisation measures.

	Key measures	Key resources	Further reading
Fossil capture	CCS, electrification	Fossil hydrocarbons, renewable electricity, CO_2 transportation and storage infrastructure	Saygin and Gielen [30], Cefiq [27], IEA [7]
Green hydrogen	CCU/green H_2 and derivatives	Renewable electricity and CO_2, H_2 infrastructure	Kätelhön et al. [29], Galán-Martín et al. [31], IEA [7], Saygin and Gielen [30]
Bio	Replacing fossil feedstocks with bio-based feedstocks	Sustainable biomass	Saygin and Gielen [30], Galán-Martín et al. [31]
Circularity	Collection, sorting, mechanical and chemical recycling	Collection systems, renewable energy	Ellen McArthur Foundation [37], The Pew Charitable Trusts and SYSTEMIQ [38]
Less-is-more	Reduced consumption, substitution	Alternative materials (often bio-based)	Ellen McArthur Foundation [37], The Pew Charitable Trusts and SYSTEMIQ [38]

petrochemical industry to radically reduce its GHG emissions – will result in changes in technological and social structures and processes. The necessary shift away from fossil feedstocks will likely drive a change in the geography of production and raw material supply, and the transition will reallocate costs and benefits in different ways, depending on how it is managed. Research within the field of sustainability transitions is paying increasing attention to the notion of justice and the concept of a 'just transition' [23,39–41]. This concept originated in the U.S. labour unions in the 1970s and was made explicit by unions in the chemical sector in the United States and Canada, respectively, in the 1990s [42]. In the last two decades, it has become part of national labour unions' and international labour union federations' agendas on the environment and environmental justice [42,43], in their efforts to not only address the social concerns of workers and other marginalised groups but to fuse this with environmental concerns and to identify paths towards social justice for people and ecological justice for nature. Ciplet and Harrison [43] (p. 437) suggest that the concept of a 'just transition' can 'potentially bridge between movements focused on economic concerns with those concerned with environmental sustainability'. Hence, the concept of a just transition implies that economic, environmental and social aspects must be addressed in parallel.

The local context has been emphasised as essential for transformation in general [44] and for a just transition in particular [23]. Hansen and Coenen [44] highlight the importance of (a) visions and policies, (b) informal localised institutions, (c) local natural resource endowments, (d) local technological and industrial specialisation and (e) consumers and local market formation. The researchers call for more research on the geography of transitions, with the aim of exploring similarities and differences across places and scales. Along the same lines, Upham et al. [45] point to the importance of three themes related to geographical space: (a) politics, space and institutions; (b) new processes and procedures; and (c) acceptance and resistance. An example of this is the creation of the photovoltaics (PVs) market in Germany, which is often attributed to the introduction of feed-in tariffs. However, one policy instrument cannot fully explain this development, and Dewald and Truffer [46] show that another part of the explanation is that a few German states initiated a transformation of their energy systems as a reaction to the Chernobyl catastrophe. The researchers show that the development at the local level in these states laid a foundation for the development of the national feed-in policy instrument. This finding shows that the local and regional context largely forms the prerequisite for transition, and that careful attention must be paid to this context in order to understand transitions.

Along the same lines the EU introduced a 'Just Transition Mechanism' in its European Green Deal (launched in December 2019), which focuses on the regional context and aims to ensure that a transition to a climate-neutral economy leaves no one behind [47]. This mechanism focuses on the regions and sectors that are at risk of being strongly affected by the climate transition, due to a dependency on fossil fuel or industrial processes that cause large GHG emissions. The mechanism's instruments include a dedicated scheme under InvestEU, a loan facility at the European Investment Bank, and a Just Transition Fund, which focuses on the economic diversification of the regions most affected by the climate transition, with particular attention on the reskilling and active inclusion of their workers and jobseekers [48]. A condition for support from all Just Transition Mechanism instruments is that the affected Member States develop Territorial Just Transition Plans, which – as the name indicates – takes as its starting point the regional context for the different transition processes. Based on the work with four such plans in Sweden, Moodie et al. [49] conclude that 'balance between the technical, social, and spatial elements of a just transition is needed if policies are going to meet the requirements of local and regional citizens and provide sustainable socio-economic growth and environmental protection, without risks of delocalising energy-intensive processes to other regions'.

However, industry structures and the technological pathways that are involved in their transition processes are part of socio-technical regimes, which often have global characteristics. Fuenfschilling and Binz [50] explain how industries are often global in terms of their actor networks and institutional rationalities. For instance, industries are often organised on an international scale, such as in the form of multinational corporations and their subsidiaries [51,52]. Fuenfschilling and Binz [50] also describe how, as a result, we often see industrial transition processes following similar trajectories despite being located in different parts of the world and having diverging material and institutional prerequisites for development and change. The researchers use the case of the water sector in China to illustrate how this sector has evolved similarly to the global regime, despite its specific national context.

Moreover, while the focus of the just transition discussion was initially on experiences from fossil-dependent regions and communities in Europe and North America, the scope of this discussion has gradually widened. Atteridge et al. [53] describe how, in order to expand the utility of the concept of a just transition in the global context, it is important to recognise that the socio-economic and political context in many developing countries presents challenges to the successful design and implementation of climate policy. This includes, for example, having a large share of informal workers, limited energy access and a lack of social safety nets. Cronin et al. [54] discuss the justice implications of 1.5 °C-consistent emission pathways and how deep and fast cuts in global GHG emissions will bring enormous collective benefits; however, they also note the risk that mitigation action will lead to significant disruptions and losses to some groups and countries. Robinson and Shine [55] stress that, unless justice concerns are properly addressed, actions to address climate change also risk exacerbating injustices associated with the rights to development, resource sovereignty, food security and livelihood. These tensions are continuously present in the UNFCCC negotiations, not least when it comes to discussions on global effort sharing and international climate financing.

2.3. Indicators of prerequisites for change and the potential for a just transition

Radically reducing GHG emissions from the petrochemical industry within a timeframe of less than three decades will require parallel efforts to avoid investments in new fossil-based capacity and to retire or repurpose existing fossil production capacity while scaling up alternative processes. The societal structure in which a technology or an industry is embedded has been shown to be critical for shaping both technological trajectories [56,57] and industry transitions [58]. To understand the potential and barriers for transition, it is necessary to simultaneously pay attention to economic, environmental and social aspects, as well as to the multiscale dynamics of how the development of these aspects unfold on various levels. In the following, we present three categories of indicators that we suggest could be used to grasp this perspective and to understand the contextual prerequisites for a just transition: (a) the availability of natural resources, (b) petrochemicals' role in the economy and (c) the socio-political landscape.

With respect to the *availability of natural resources*, we focus on both *fossil resources* that could motivate continued operation and *renewable resources* that could motivate and enable a transition. Johnsson et al. [59] discuss how the regional distribution of fossil fuel endowments (coal, oil and gas) and existing and planned fossil-based infrastructure must be considered when devising transition strategies. Access to large reserves of oil and gas poses a challenge from a transition perspective. A large number of newly announced petrochemical projects are coming from regions with large resources of either oil or gas, the so-called 'producer economies' or 'petrostates' [60]. The term 'petrostates' signals that the political economy in these states have largely been formed by the access to fossil fuel resources, where the prime objective of the state is to capture and distribute oil and/or gas rents [61]. Investments into petrochemicals can be seen as a reproduction of existing institutional patterns and oil and/or gas dependencies. The future of fossil-based energy revenues is generally identified even in producer states as being at risk due to climate policy measures, but the fact that the same risks apply also to petrochemical production seems to be less acknowledged.

While incumbent firms in the process industry tend to be deeply embedded in the material, economic and socio-political contexts of which they are a part [62,63], it is not unthinkable that, if the world acts decisively to limit carbon emissions, the 'rules of the game' may change considerably. In a carbon-constrained world, competition from regions and countries with low-cost and abundant renewable energy resources will increase. Thus, while access to cost-competitive and reliable fossil fuel supply has traditionally been a competitive advantage in the petrochemical industry, a push for the decarbonisation of the global economy could lead to a change in the geography of production and raw material supply, where favourable conditions for renewable power production, access to sustainable biomass resources and carbon dioxide storage capacity could give a competitive edge (see e.g. Ref. [30]). This could be an opportunity for countries and regions that have not previously held major stakes in the petrochemical industry [64]; it could also offer a way out for fossil-rich regions and countries that also have favourable conditions for renewable energy production. There is, however, no guarantee that such a shift away from fossil hydrocarbons would on its own undo the current patterns of exploitation and dispossession that characterise the global fossil economy [65].

The second category of indicators we look at is *petrochemicals' role in the economy*. Caldecott et al. [66] list a range of factors that present economic and political challenges to the phasing out of coal. A central factor is geographical concentration, which results in strong regional economic dependency. To capture this factor, we include indicators describing *economic development* and *the petrochemical industry's role in the economy*. Difficulties of achieving labour mobility and re-allocating human capital is also highlighted as a challenge. Similarly, Spencer et al. [67] point to the important role of potentially 'stranded regions' where workers, regional governments and the regional economies more broadly are dependent on the fossil fuel industry. It seems reasonable to believe that these factors are, at least partly, applicable to the supply and processing of fossil in the petrochemical industry as well. To grasp the last two factors, we include indicators of *trade in petrochemicals and plastics* and *workforce*.

The final category of indicators we address is the *socio-political landscape*, as this involves institutions that create the rules of the game and therefore are key for putting pressure on existing regimes and thereby hindering or inducing change [68,69]. We particularly focus on *climate policy*, which can facilitate transitions in industry by providing directionality for innovation and thus reducing the risk for investments [70]. The stronger the climate policies are, or the more strongly they are backed by legal instruments, the more likely it is that they can reduce companies' risk of investment in novel technologies and facilitate a transition [70]. The Paris Agreement currently sets an ambition for emission reductions; however, policy implementation occurs at the national level. Thus, the main thrust in the global climate policy arena at present stems from domestically or regionally driven policies [71]. At the same time the national diversity of policy ambitions and instruments has been reinforced, including instruments such as cap-and-trade systems, carbon taxes, and sectoral and regulatory policies aimed at improving energy efficiency and developing and deploying renewable energy sources and zero-carbon technology [72,73].

While there are examples of how non-participatory authoritarian regimes can fast-track technological development and technological change processes (see e.g. [74]), there are reasons to believe that a recognition of political rights, civil liberties and labour rights increases the chances of creating legitimacy for change and potentially building bottom-up pressure for a timely climate transition. To grasp the broader local social context that is central for justice in transition processes [23,75,76], we also include an indicator of *civil liberties, labour rights and social protection*. An example along this line is that a well-developed system of social dialogue and the active involvement of social partners in policymaking in general – and the involvement of unions in particular – in shaping the restructuring strategy have historically been important in coping with structural change in the economy [77]. A summary of our categories and of the indicators used to assess the prerequisites for escaping the current fossil lock-in within the petrochemical industry and for enabling a just transition is presented in Table 2.

3. Method

This study combines an overview of global and regional trends in the petrochemical sector with a more in-depth mapping and exploration of the prerequisites for escaping the current fossil lock-in of the petrochemical industry on a country level. This section outlines the scope of the study and the methodology used for data collection and evaluation.

3.1. Selected countries

The focus of this study is on the 10 countries or regions with the highest active petrochemical capacity in the world: China, the United States (US), India, South Korea, Saudi Arabia, Japan, Russia, Iran, Germany and Taiwan[1] [88]. While all these countries have major petrochemical industries, the national and local contexts vary considerably in terms of access to natural resources and position in the global economic web, in terms of political and economic priorities and with respect to attitudes to climate governance.

[1] Note that Taiwan remains a contested geographic entity. However, its high concentration of petrochemical production capacity makes it a relevant geographical region for the purpose of this study.

Table 2
Summary of the categories and indicators applied in the analysis.

Category	Indicator	Rationale
Availability of natural resources	1. Access to fossil-based energy and raw material 2. Access to renewable energy and raw material	We include indicators of both fossil and renewable resources, as these form part of the prerequisites for the transition of the petrochemical industry. Dependencies on fossil resources might create a lock-in to the current industry structure [59,60]. As described above, there are various technological routes for producing chemicals with net-zero CO_2 emissions based on biomass, CO_2 utilisation, recycling, and CCS. However, all these routes are potentially limited by the local availability of energy and natural resources [34]. The presence of renewable resources is an indication of possibilities and motivation for transition based on these sources [7,64].
Petrochemicals role in the economy	3. Economic development	We include this indicator to obtain a general understanding of the economic development in the studied countries in general and the petrochemical industry's role in the economy in particular. The rationale for including the general economic development is that the cost of a transition is most likely easier to carry for a nation with a high GDP per capita. In developing countries, industrialisation will continue to play a key role in their growth [78], which can hinder transition.
	4. Petrochemicals' share of the economy	The petrochemical industry's role in the economy is indicated in terms of the share of chemical sales in the studied economies. The rationale for including this indicator is that it can be seen as a measure of the importance of the petrochemical industry for the nation. We assume that high importance can be a potential hindrance to transition. Not transforming while other regions do carries a risk of potentially 'stranded regions', where regional economies remain dependent on an obsolete fossil fuel industry [67].
	5. Trade in petrochemicals and plastics	The petrochemical industry is deeply intertwined with the plastics value chain [79]. Here, plastics trade data is used to illustrate what role the studied countries play in different parts of the plastics production chain. From a national perspective, there can be several reasons for promoting a domestic petrochemical industry, such as to maximise the value of domestic fossil resources [60] and to promote local upstream production [80]. As traditional demands for fossil fuels are set to decline, chemicals manufacturing has increasingly become an attractive option to make up for losses in other markets [6,7,10]. Plastics (40.1 % of the mass output) together with fertilisers (33.5 % of the mass output) currently account for the vast majority of global chemical product end use [11].
	6. Workforce	This indicator describes the current workforce in the petrochemical industry and its importance for the studied economies. Transitions and changes in production will impact the workforce through the loss of jobs, changing of jobs, and creation of new jobs, and because new jobs might not be created at the same locations as the current ones [23,81].
Socio-political landscape	7. Climate policy	This indicator gives an indication of the stringency of a country's climate policy, including climate policy targets, strategies, and measures that can execute external pressure on industry actors and, by doing so, stimulate actions for transition [68,69,82]. We particularly focus on climate policy at the national level, since this is key for setting direction and investment for transition in the industry [70].
	8. Civil liberties, labour rights and social protection	Respect for civil liberties, labour rights and access to social protection have been shown to be important for creating legitimacy for change, preventing the overriding of local democracy and handling the conflicts of interest that are associated with low-carbon energy transitions [19,83,84]. Conversely, human rights violations not seldom go hand-in-hand with environmental injustice [85] and the subversion of social and environmental movements [86,87]. Here, indicators for civil liberties, labour rights and social protection are used to provide indications of the potential for building bottom-up pressure and of the societal preparedness to handle the socio-economic stresses involved in structural change. Together, these indicators are used as a basis for an assessment and discussion of the potential for a just outcome of the petrochemical industry transition in the studied countries.

3.2. Data collection

Here, we present the data collection and its limitations for each of the indicators.

3.2.1. Availability of natural resources

3.2.1.1. Access to fossil-based energy and raw material. Data describing fossil-based energy production– that is, the annual fuel production (oil, coal and natural gas) – of the analysed countries was gathered from the United States Energy Information Administration [89]. The only data gaps were for countries where reserves or production of oil play a minor part in the country's economy – that is, South Korea, Japan and Taiwan.

The indicator chosen to express access to fossil-based raw materials is the corresponding carbon content (metric tons per year) of fossil fuel production (oil, coal and natural gas). For oil, a carbon content of 85 % was assumed [90], and one barrel of oil was assumed to contain 0.14 tons of oil. For coal, the carbon content was assumed to be 77 % [91]; for natural gas, it was assumed to be 71 % (the stochiometric composition of methane).

3.2.1.2. Access to renewable energy and raw material. For renewable energy, the IRENA national energy profiles [92] were used to determine current renewable electricity production levels; however, a mix of different sources were used to estimate the future potential. Zhou et al. [93] estimate country-by-country hydropower potential (Wh) based on runoff, stream flow data, turbine technology performance, cost assumptions and considerations of protected areas. This estimation covers all 10 countries except for Saudi Arabia, where, although rainwater dams have some potential for hydropower generation, the total potential is likely to be negligible due to the lack of continuously running rivers. Data on global solar power potential on a country level was retrieved from ESMAP [94] which estimates the 'practical PV potential' by combining the theoretical potential with considerations of the air temperature affecting the system performance, the system configuration, shading and soiling, and topographic and land-use constraints. This data was combined with assumptions of the nominal power (kWh/m^2) of PV panels to estimate the annual energy potential (Wh). Although there are obvious limitations in assuming that all practically utilisable area is used (e.g. neglecting potential barriers for grid expansions), this assumption is sufficient to give an idea of the order of magnitude of the potential. For offshore wind power, the annual mean wind speed was used in a study by the World Bank [95] to estimate the potential (W) of both bottom-fixed (water depths up to 50 m) and floating (water depths of 50–1000 m) wind power in the economic exclusive zones of countries, using a wind speed of 7 m/s at a height of 100 m as the lower cut-off limit. Since no similar study was found for onshore wind power potential (W), these values were estimated by multiplying the mean power density (W/m^2) of the countries from the Global Wind Atlas by the available land area (m^2) of the same countries, making the same assumption regarding the share of available land area as made in Ref. [94]. The potential electricity production (Wh) from onshore and offshore wind power was then estimated by assuming that the power is fully utilised for 8760 h/yr. The assumption that the same share of land area is available for onshore wind power as for solar power means that these potentials overlap and are likely not possible to realise fully.

The indicator chosen to represent the availability of renewable raw material is the potential for renewable carbon in a country, based on biomass potential. This includes estimations of the total biomass potential and a more restrictive estimate of the biomass potential from forestry and agricultural residues. Estimations of biomass potential were collected from the national energy profiles from IRENA [92], looking at the net primary production (NPP) as an estimate of available biogenic feedstock. Although this provides a rough estimate, it can be used to give an indication of the relative prerequisites for a country to replace fossil-based carbon with biogenic carbon in its petrochemical industry. The residue potential is based on a study by Deng et al. [96], which estimates the potential transport biofuel production from agricultural and forestry residues in 55 countries. Since the residue potential is expressed in energy potential (PJ), an average carbon content of biodiesel and bioethanol of 0.020 kg/MJ is assumed to convert the residue potential into carbon potential. Furthermore, to complement the lack of data for South Korea, Saudi Arabia, Japan, Iran and Taiwan, this value is scaled from the total biomass potential by assuming that the ratio between the total biomass potential and residue potential for these five countries is the same as the average ratio of the other five countries in this study (1.5 %).

3.2.2. Petrochemicals' role in the economy

3.2.2.1. Economic development and petrochemicals' share of the economy. The World Bank's World Development Indicators [97] were used to describe the economic development and current economic status across the studied countries. The data on the value of chemical sales in the individual countries was retrieved from the German chemical industry association Verband der Chemischen Industrie [98].

3.2.2.2. Trade of petrochemicals and plastics. Data on trade of petrochemicals and plastics during 2011–2020 was gathered from UNCTAD STAT [99], including trade statistics over the plastic value chain (first compiled by Barrowclough et al. [79]). The data is available in categories for each step in the value chain, which in turn include several different commodities. Data was available for the later steps of the value chain but not for the first steps in the value chain (i.e. raw fossil fuels, feedstocks and additives). For further information on the commodities included in each category, see Ref. [79]. Data for Taiwan is not included in the database.

3.2.2.3. Workforce. The data on the size of the workforce in each country and on labour in the petrochemical industry was retrieved from the United Nations Industrial Development Organisation [100], from the International Labour Organisation (ILO) [101] and from the ILO's Department of Statistics [102].

3.2.3. Socio-political landscape

3.2.3.1. Climate policy. To illustrate how the stringency of climate policy differs between the studied countries, we compiled information on:

- Long-term and interim climate targets (including legal status),
- Overall rating of governmental policies and action, and
- Carbon pricing instruments targeting the petrochemical industry.

The data on country-level climate targets (including legal status) and net-zero pledges comes from a database administered by Net Zero Tracker [103]. The overall rating of governmental policies and action comes from the Climate Action Tracker (CAT) by Climate Analytics and NewClimate Institute [104]. The CAT rating method evaluates a broad spectrum of government targets and actions to reduce GHG emissions in line with the Paris Agreement temperature limit. The rating of policies and action evaluates the extent to which governments are putting real policies and action in place, in line with global least-cost mitigation pathways or fair-share principles. Information on the existence/enforcement and status of carbon pricing mechanisms comes from the World Bank [105] and IEA [106].

3.2.3.2. Civil liberties, labour rights and social protection. We used Freedom House's global freedom score as an indicator of the extent to which political rights and civil liberties are acknowledged in law and in practice within a country [107]. The global freedom score builds on an aggregated assessment of the real-world rights and freedoms enjoyed by individuals in 195 countries across the world. The aggregate score builds on a weighting of 10 political rights indicators and 15 civil liberties indicators. The combination of the overall score awarded for political rights and the overall score awarded for civil liberties, after being equally weighted, determines a status of *free*, *partly free*, or *not free* [108].

The Centre for Global Workers' Rights [109] Labour Rights Indicators are used to describe the extent to which basic labour rights are recognised in law and in practice in the studied countries. The Labour Rights Indicator score is based on an assessment of 108 evaluation criteria grouped in five categories [110]: (I) fundamental civil liberties; (II) the right of workers to establish and join organisations; (III) other union activities; (IV) the right to collective bargaining; and (V) the right to strike.

The data describing country-level expenditure on social protection systems was collected from the ILO's World Social Protection Report 2020 [111]. This data includes government expenditures on services and transfers provided to individuals and households, as well as expenditures on services provided on a collective basis including, for example, sickness benefit, child care, elderly care and unemployment compensation.

3.3. Basis for the evaluation of indicators

To provide an overview of what the national contexts may mean for the chance of escaping the current fossil lock-in in the petrochemical industry in each country, we conducted a qualitative evaluation for each indicator to determine whether the material, economic and socio-political contexts in each nation are likely to contribute to opening up for change or to reinforcing the current lock-in. These indicators and their evaluation criteria are summarised in Table 3.

4. Results

In this section, we first present a global overview that motivates our selection of countries and positions their national challenges within a global context. This is followed by a presentation of the results from the assessment for each category of indicators: *availability of natural resources*, *petrochemicals' role in the economy* and *socio-political landscape*. For each of the themes, the implications of the indicator results are discussed in terms of the prerequisites for change and the potential for a just transition in the respective countries.

4.1. Global overview

Expansion of the modern petrochemical industry largely took place after WWII, with North American and European producers dominating production and sales during much of the 20th century. As shown in Fig. 1(a), a large share of capacity expansion in the past decade or more has taken place in China, the rest of Asia and, to some extent, in the Middle East. Despite not being directly reflected in the chemical sales

Table 3
Summary of indicators and their evaluation criteria.

Category	Indicators	Evaluation criteria
Availability of natural resources	1. Access to fossil fuel-based energy and raw material	Large domestic fossil resources = tend to reinforce the current fossil lock-in Limited domestic fossil resources = indicates an opening for change
	2. Access to renewable energy and raw material	Significant potential for renewable electricity production and/or supply of biomass = indicates an opening for change Limited potential for renewable electricity production and/or supply of biomass = reinforces the current lock-in
	3. Economic development	Here, the level of economic development is assumed to provide an indication of the resources available for incentivising a transition. Manufacturing can also be assumed to be relatively more important in countries that are in earlier phases of economic development. Developed economy (high GDP/cap) = contributes to opening up for change Developing economy (lower GDP/cap) = risks reinforcing the current lock-in
Petrochemicals' role in the economy	4. Petrochemicals' share of the economy	Interpreted as an indicator of the relative importance of the petrochemical industry to the national economy as a whole. Small share of the total economy = contributes to opening up for change Large share of the total economy = risks reinforcing the current lock-in.
	5. Trade in petrochemicals and plastics	Interpreted as a gross indicator of what role petrochemicals play in the trade of the country and what role individual countries play in the global supply chain for plastics.
	6. Workforce	Interpreted as a gross indicator of the relative importance of the petrochemical industry to the national labour markets and this industry's role in the political economy.
Socio-political landscape	7. Climate policy	Stringent climate policy commitments = incentivises decarbonisation Lax/no climate policy commitments = hinders decarbonisation
	8. Civil liberties, labour rights and social protection	This indicator, or combination of indicators, shows the extent to which civil liberties and labour rights are respected and the level of social protection in each of the studied countries; taken together, it provides an indication of the potential for civil society actors to advocate for change from below and of the societal preparedness to handle the socio-economic stresses involved in structural change.

data, several expansion projects took place in North America during 2009–2018, most of which were located in the historical petrochemical clusters on the United States Gulf Coast [112]. Data on planned and announced petrochemical capacity addition suggests that the total global production capacity will continue to grow and that the bulk of this growth is expected in Asia, the Middle East and the former Soviet Union (Fig. 1(b)). As stated above, the focus of this study is on 10 countries – namely, China, the United States, India, South Korea, Saudi Arabia, Japan, Russia, Iran, Germany and Taiwan – which together account for more than 70 % of the world's active petrochemical capacity (Fig. 2).

Plastics and plastic packaging are an integral part of the global economy, and the rising demand for plastics is the single most important driver of petrochemical production. Global plastics production grew from 2 Mt. to 380 Mt. between 1950 and 2015 [113] and is expected to more than double again over the next 30 years, unless the trend is broken [114] (Fig. 3). The same trend can be seen in the 10 countries in focus in this study, whose plastics consumption grew from 116 Mt. in 2008 to almost 168 Mt. in 2016 [115]. The major driving force of this increase in demand is China, where demand doubled during this period, making up half of the consumption; however, significant growth can also be discerned in India.

4.2. National contexts

4.2.1. Availability of natural resources

4.2.1.1. Access to fossil energy and raw material. The countries

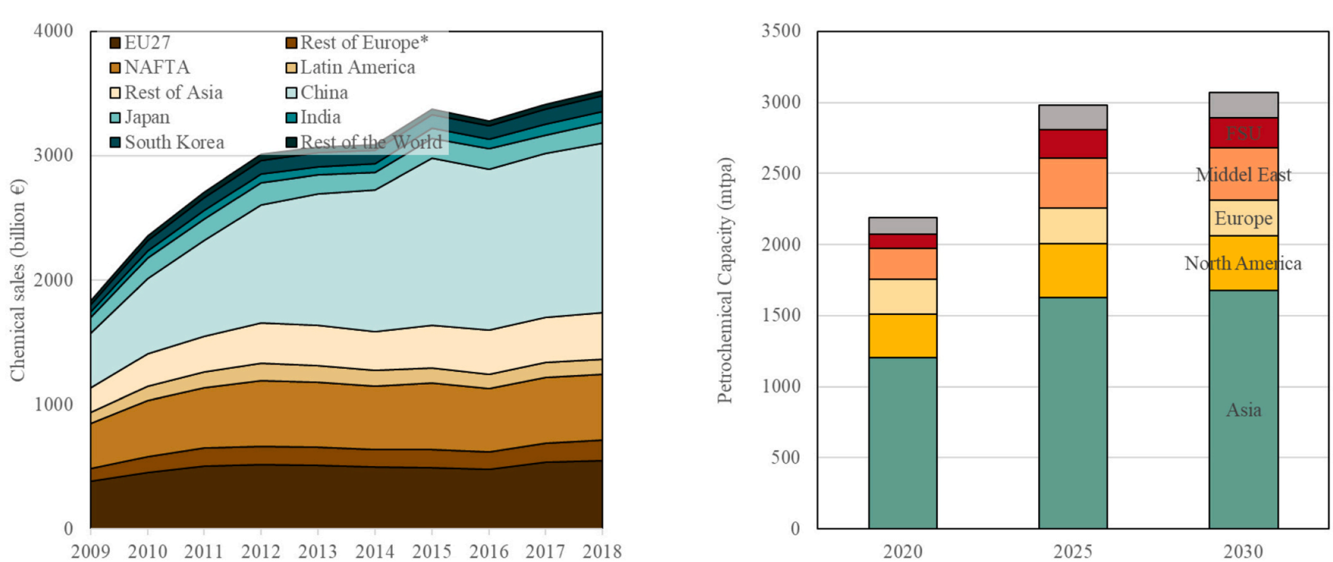

Fig. 1. (a) Development of global chemical sales (billion €) by region during 2009–2018 (based on data from Ref. [27]) and (b) planned capacity expansion during 2020–2030 (based on data from Ref. [88]).

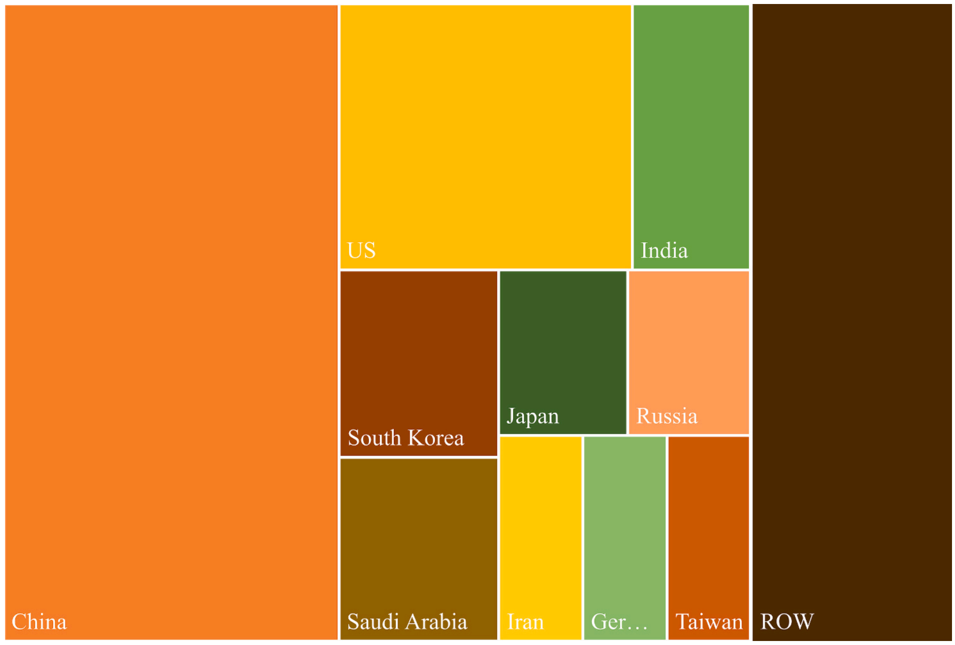

Fig. 2. Share of global petrochemical production capacity of the 10 countries with the highest active petrochemical capacity in the world: China (33 %), the United States (US) (12 %), India (5 %), South Korea (5 %), Saudi Arabia (5 %), Japan (3 %), Russia (3 %), Iran (3 %), Germany (3 %) and Taiwan (3 %). The combined production capacity in these 10 countries is estimated to be 1605.2 Mt/yr (based on data from Ref. [88]).

dominating the petrochemical industry in many cases have large reserves and significant production of fossil fuels, with the 10 countries included in this study making up half of the top 10 producers of oil, coal and natural gas. Fig. 4 shows the production of fossil fuel for each country, illustrating the heterogenous characteristics among these nations. Countries such as the US, Russia and Saudi Arabia have large-scale production of both oil and gas, whereas the production level in Germany is much more limited. China has large-scale fossil fuel production, but most of this is coal, which – compared with oil- and natural gas-based production – has higher equipment costs and lower selectivity

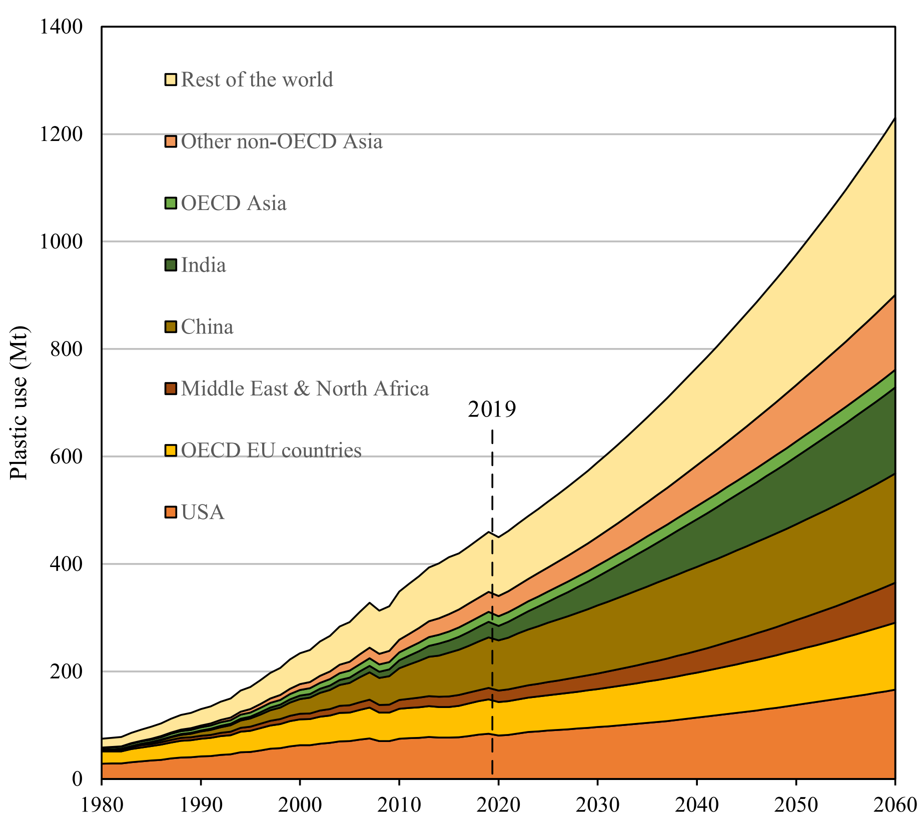

Fig. 3. Global plastic use (Mt). Numbers on the left side of the graph give estimates of regional plastics use up to the year 2019 (dashed line). Numbers on the right side give projections of the development of plastics use, per region, during the period 2020–2060 (based on data from Ref. [114]).

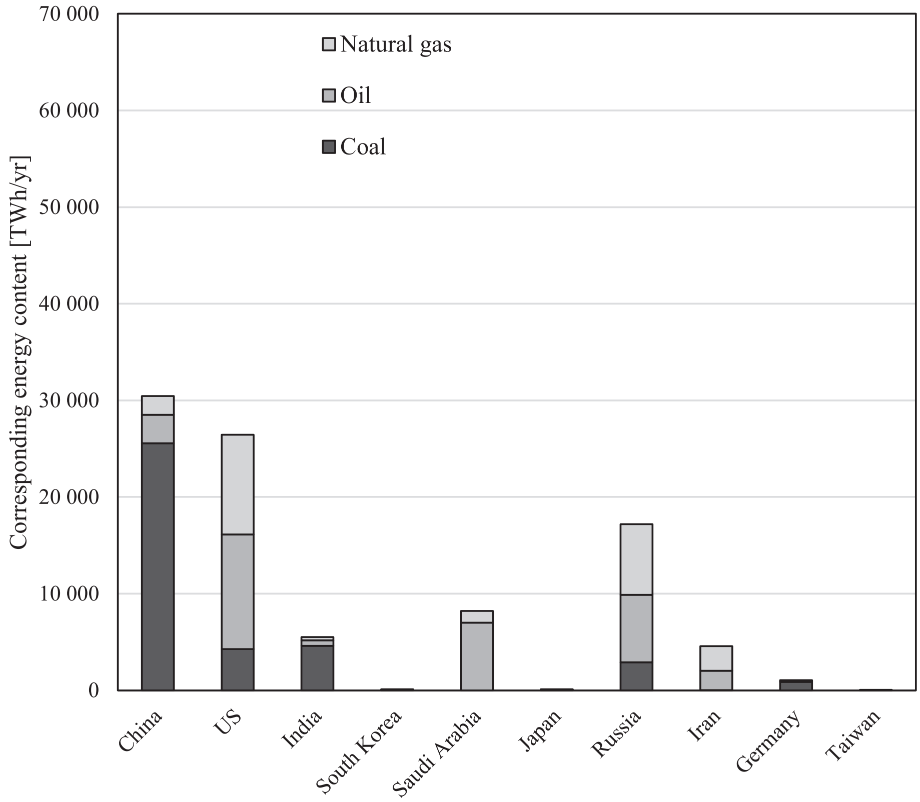

Fig. 4. Annual fossil fuel production expressed in terms of energy content (TWh/yr). Based on data from Ref. [89].

[7]. India has a substantial fossil fuel production, but almost all of it is coal; Iran has a similar total production, which mostly consists of oil and gas. It should also be noted that the numbers for Iran are likely impacted by the trade sanctions imposed on Iran by mostly Western countries since 1979 [116]. Data for coal production in Saudi Arabia and Taiwan is not available from the same sources used above, but coal production in these nations is negligible, according to other sources [117,118].

While it is difficult to discuss the conditions for a transition of the petrochemical industry in these countries based on their current fossil fuel production alone, some insights can be drawn from the recent trend in which 'petrostates' are diversifying their economy by moving into petrochemicals. Although this pattern is not necessarily set to continue, there is reason to believe that countries rich in fossil fuels (particularly oil and gas) have less incentive from a purely economic point of view to enforce or promote a transition of their petrochemical industries in a way that will decrease the demand for their fossil resources. Thus, countries such as Saudi Arabia, Russia and Iran would be the least inclined to transition away from a fossil-based petrochemical industry, whereas such a transition might be easier for countries such as Germany, Japan, Taiwan and South Korea. While the United States is not as dependent on revenues from oil and gas and may therefore not qualify as a 'petrostate', it can still be considered a 'producer state', considering its significant production and resources of fossil fuels, and may therefore have similar lock-in issues.

4.2.1.2. Access to renewable energy and raw material. Although fossil-based petrochemical capacity dominates the current market, many of the envisioned pathways for the climate transition of the petrochemical industry require large-scale renewable resources (Table 1). Fig. 5(a) illustrates how, in many cases, the electricity for replacing petrochemical capacity with electroplastics could be covered by the potential renewable electricity sources of those same countries – including countries that are currently rich in fossil resources. However, the figure also includes the current level of renewable electricity production, illustrating that considerable increases would be required for such a transition. Moreover, competition with other sectors of society for renewable electricity further complicates the situation.

To replace fossil-based petrochemical production with renewable capacity, some form of alternative carbon source must be used. In the case of plastic recycling, no new carbon source is required; however, the production of renewable electroplastics and bio-based plastics requires carbon to be supplied from some form of biogenic source. While a variety sources may exist, they can all be estimated in terms of their carbon content. Fig. 5(b) illustrates how the corresponding carbon content of the petrochemical capacity of the 10 studied countries relates to the potential biogenic carbon sources of these countries, in terms of both the total potential (based on the net primary production) and the carbon available from agricultural and forest residues. Although the total biogenic carbon potential is sufficient to replace the petrochemical capacity of most countries, the figure shows that this potential is clearly limited if the carbon source is restricted to residues.

4.2.1.3. Implications for change and a just transition. The availability of natural resources has more implications for the prerequisites for change in general than for the potential for a just transition in the studied countries. As suggested by the literature on petrostates (see e.g. Ref. [60]) and fossil-rich countries (see e.g. Ref. [59]), the countries rich in fossil resources (i.e. the USthe United States, Saudi Arabia, Russia and Iran in particular, but also China) can be expected to be less inclined to shift away from fossil fuels than countries with scarce fossil resources (i.e. Germany, Japan, South Korea and Japan in particular, but also India to some extent). There is a risk that a lock-in of industry structure and the reproduction of institutional patterns could be the outcome of such countries' desire to prolong the use of resources, diversify the economy and stabilise political regimes. On the other hand, several of these countries have access to significant renewable resources, which might offer a way out of a fossil lock-in [7,64]. This is especially the case for China, the US, Saudi Arabia, Russia, India and Iran, although the

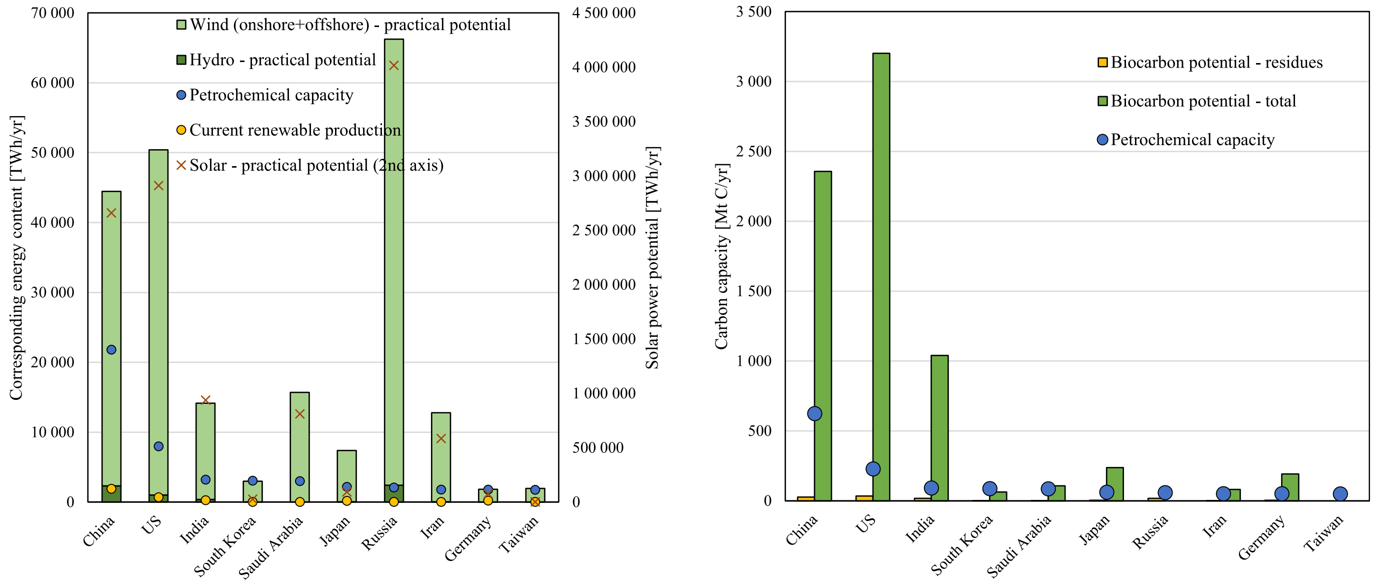

Fig. 5. (a) Renewable electricity production today (yellow dots); estimated practical potential for wind (light green bars), hydro (dark green bars) and solar power (red crosses); and petrochemical capacity expressed in corresponding electroplastic electricity demand (blue dots). (b) Petrochemical capacity for each of the studied countries expressed in carbon content (blue dots), estimated total biogenic carbon potential (dark green bars) and agricultural and forest residues potential (yellow bars). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

competition for these renewable resources from other sectors must also be taken into consideration, along with the difference between renewable potential and actual realised renewable production.

4.2.2. *Petrochemicals' role in the economy*

4.2.2.1. Economic development and petrochemicals' share of the economy. Fig. 6 provides an overview of the economic development in recent decades and the relative value of chemical sales in the selected countries. The studied countries can be classified [119] as having *developing economies* (i.e. China, India, Saudi Arabia, the Republic of Korea, Iran and Taiwan), *economies in transition* (Russia) and *developed economies* (US, Japan and Germany). Fig. 6(a) shows how economic development and current economic status vary, both across countries and in relation to the world as a whole. Most of the studied countries experienced greater economic growth than the world average during the period 1990–2020, with the exceptions of India and Iran. Fig. 6(b) plots the relationship between GDP per capita and the value of chemical sales in relation to total GDP in the studied countries. In all these countries, the value of chemical sales in relation to total GDP is greater than the global average. The graph also indicates that the value of chemical sales in relation to the economy is higher in the countries with a relatively lower GDP per capita.

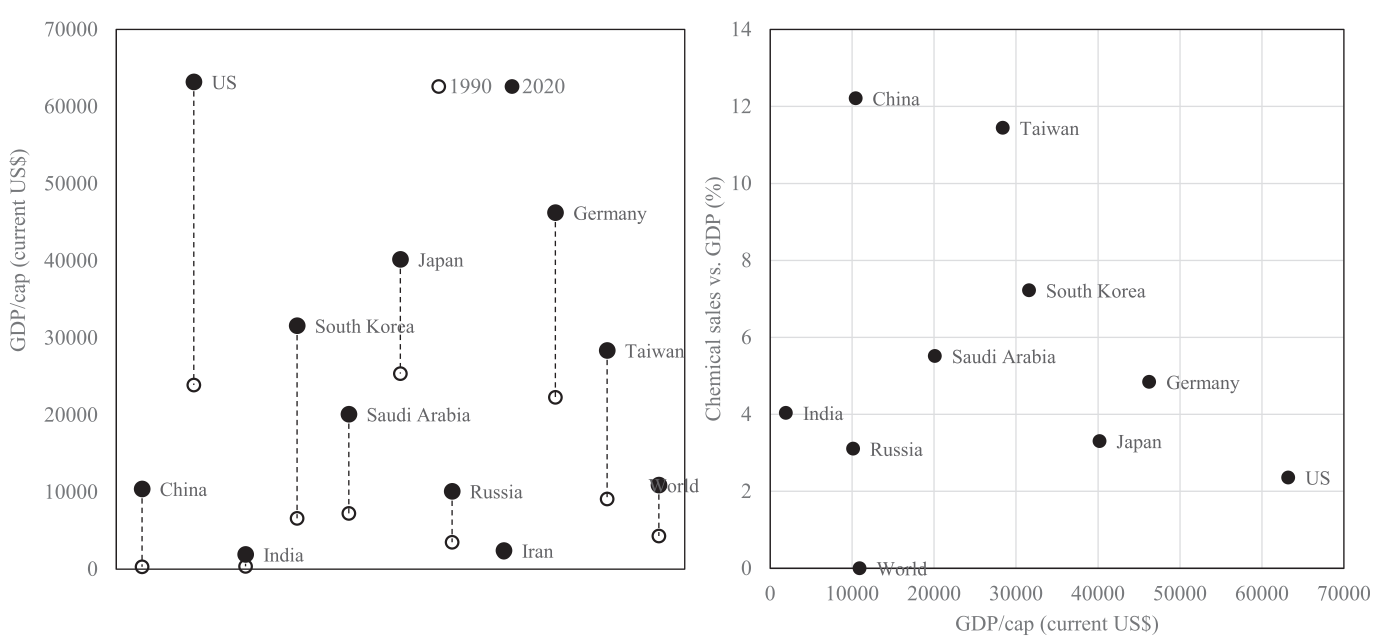

Fig. 6. (a) Economic growth during 1990–2020 in the 10 countries with the highest active petrochemical capacity and in the world as a whole (expressed as growth in GDP per capita) (based on data from Ref. [97]). (b) Mapping of GDP/capita and the value of chemical sales in relation to total GDP in the selected countries (based on data from Refs. [97, 98], data on Iran unavailable).

4.2.2.2. Trade. The diverse situations of each country's trade in plastic-related petrochemicals are shown in Fig. 7, which illustrates the trade flows across the value chain of plastics, although the most upstream parts of the value chain – that is, raw feedstock (oil, gas, coal) and refined feedstock (naphtha, ethylene, propylene, etc.) – are not included here. According to this figure, Germany, South Korea and Japan can be grouped together as countries that are large exporters across the plastics lifecycle; these countries have a positive trade balance in all categories, except for a slight negative trade balance in final manufactured plastic goods for Japan. Russia, on the other hand, is a net importer across the value chain, albeit to a lesser extent than Germany. The other countries are more multifaceted; for example, China is a large net exporter of more refined forms of plastics but has a large net import of plastics in primary forms. In contrast, the United States is a major net exporter in the earlier stages of the value chain but a net importer of final manufactured plastic goods. Saudi Arabia almost entirely exports primary forms of plastics but is a net importer further down the value chain. This situation is mirrored by that of India, which is an importer of primary forms of chemicals but an exporter of intermediate and final products. Although Iran is included in the graph, this data should not be viewed as reliable, due to the many years of missing data that can be connected to the frequent trade sanctions imposed on Iran.

It is possible to discern patterns by combining the observations on trade data with the observations regarding natural resources (Section 4.2.1), plastic demand (Section 4.1) and petrochemicals' share of the economy (Fig. 6). The United States and Saudi Arabia seem to be part of the trend of fossil-rich states that are approaching downstream integration with the petrochemical industry, as a way of capturing more value in the next step of the value chain. Further down the value chain, however, neither the United States nor Saudi Arabia have any significant export. Rather, despite having a large plastic demand, the United States is still a major net importer of final plastic goods, indicating an outsourcing of these later parts of the value chain. For China, the situation is reversed, with the petrochemical industry developing as an effect of an upstream integration. China's large trade deficit early in the value chain and its surplus in the later stages of the value chain reveals a country whose petrochemical industry feeds its plastics manufacturing industry, which in turn is likely driven by both a huge and growing domestic plastic demand and the export of plastic packaging and plastic goods. In Germany, Japan and South Korea, the situation is different, since these countries have neither large fossil resources nor a particularly large plastic demand. Instead, these countries' large petrochemical industry can be seen as the legacy of their being major industrial nations, which have historically been large players within downstream manufacturing industries utilising petrochemical products (see e.g. Ref. [120]). For India, the trade numbers indicate a significant industry based on primary forms of plastics, while the low export numbers further down the value chain can likely be explained by the large domestic demand for plastics absorbing most of this production. The Russian numbers appear to show a country with comparatively little industrial activity, in both primary forms of plastics and downstream plastic products, which can be a sign that Russia's large share of petrochemical production focuses on ammonia for fertiliser production.

4.2.2.3. Workforce. Fig. 8 illustrates the number of employees in the chemical industry and the share (in percent) of workers in the petrochemical industry in relation to the labour force as a whole in each of the studied countries. The most comprehensive estimate of the number of employees in the global petrochemical industry we were able to retrieve comes from ILO [101], which estimated that 11.5 million people were employed in the global chemical, pharmaceutical, and rubber and tyre industries in 2006. Of these, 4.0 million were employed in the basic chemical industry (basic chemicals, fertilisers and plastics in primary forms), 5.4 million worked in other chemical industries (e.g. pesticides, paints and pharmaceuticals) and 2.1 million were employed in the rubber industry. In the countries in focus in this study, the total employment in the petrochemical industry was 5.3 million on average (during 2015–2019), corresponding to 46 % of the global petrochemical workforce (in 2006). However, the petrochemical workforce only constitutes 0.1–0.6 % of the labour force in the studied countries (0.3 % of

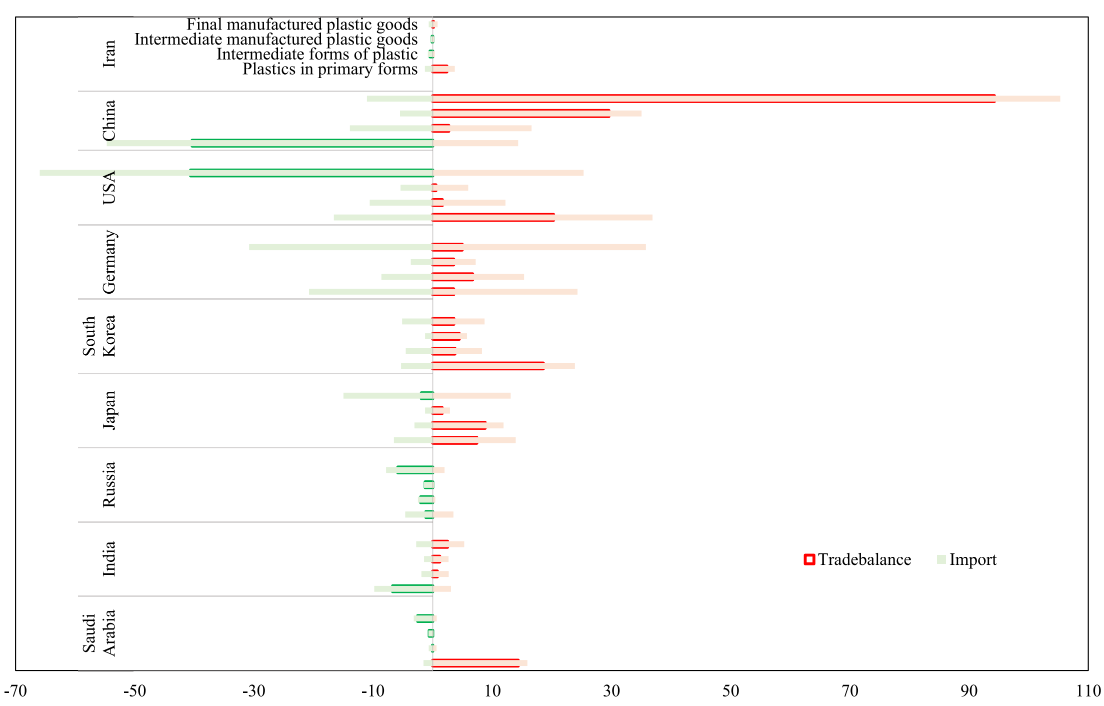

Fig. 7. Mean annual (2011−2020) trade values (import, export and trade balance) of plastics across the value chain for the 10 studied countries. The trade balance is colour coded, where red represents a positive balance (net exporter) and green represents a negative balance (net import) (Based on data from Ref. [99]). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

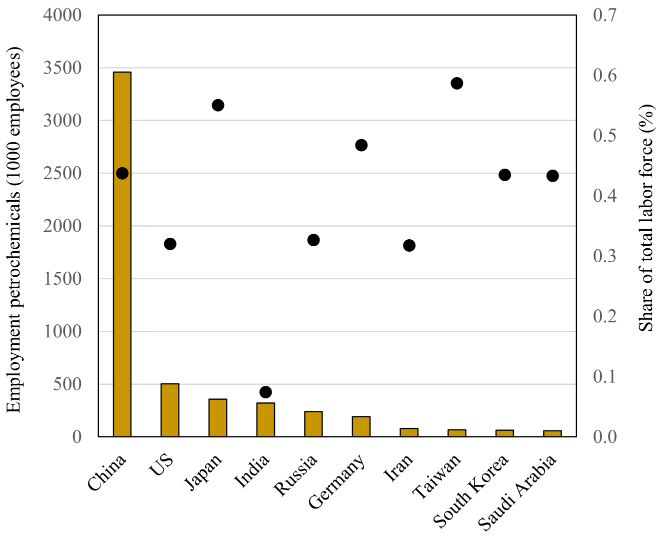

Fig. 8. Number of employees (average during 2015–2019) in the petrochemical industry overall (expressed as 1000 employees) in the studied countries. Black dots indicate the share (in percent) of workers in the petrochemical industry in relation to the labour force as a whole in each country.

the global labour force). As a comparison, estimates suggests that 106 million workers (2.3 % of the global workforce) were employed in global plastics production in 2015 [121]. Cabernard et al. [121] report that there has been a recent trend in high-income regions, such as the EU and the US, to outsource the low-paid steps in the plastics production value chain to lower income regions and to focus on the higher value-adding steps of manufacturing plastics into finished products. Workers employed in the petrochemical industry represent a relatively small share of the total workforce, both globally and in the countries assessed here. However, since the petrochemical industry in many cases is clustered into major production units that are geographically concentrated, the role of the petrochemical industry can still be considerable in local and regional economies as a source of employment [122].

4.2.2.4. Implications for change and a just transition. This category of indicator provides a gross illustration of the role of the petrochemical industry in the respective national economies. Here, the level of economic development is used as a crude indicator of the resources available for incentivising a transition in the respective countries. This indicator suggests that the potential for change is higher in high-income countries like the US, Germany, Japan and South Korea than in low-income counties like India, Iran and Russia, where economic resources to support a transition away from fossil fuels in the petrochemical industry can be expected be more constrained. It is reasonable to assume that the same is true for these countries' ability to provide financial support to the workers and communities that may be impacted by such a transition. Here, the value of chemical sales in relation to the total GDP is used to give an indication of the relative importance of the petrochemical industry to the economy as a whole in the studied countries. The data clearly shows (Fig. 6) that the petrochemical industry plays an important role in all the studied countries; however, it also shows that the relative importance of this industry varies significantly across countries. In China, the value of chemical sales corresponds to more than 12 % of the GDP, while the corresponding figure in the United States is just over 2 %. In our interpretation, the structural implications of a shift away from the current production process – and therefore the hesitancy towards change – can be expected to be greater in countries such as China, South Korea and Taiwan than in countries where the petrochemical industry's share of the total economy is less pronounced. The assessment of the country-level data on trade in petrochemicals and plastics is used as an indicator of the extent to which the studied countries are involved downstream in the value chain for plastic (which, together with fertilisers, accounts for the bulk of global petrochemical use [11,79]. In both the United States and Saudi Arabia, the trade balance likely acts to hold back – rather than drive – a transition away from fossil fuels, as the valorisation of fossil resources is a major driving force behind the emergence of the industry. In China, on the other hand, the limited fossil resources of the country (except for coal) provide better conditions for a transition, as it would benefit the trade balance of the country if China were to switch to using renewable energy and feedstock for this industry. However, China's large and growing domestic demand for plastics, combined with its large export of products further down the value chain, means that a transition based on a decrease in petrochemical output is less likely. For countries such as Germany, Japan and South Korea, the situation is more beneficial from a trade and raw materials point of view, as these countries have a more limited domestic demand for products; moreover, a switch from fossil-based to renewable energy and feedstocks could make these nations' petrochemical and (likely also) manufacturing industry less dependent on imported resources. The total number of employees in the petrochemical industry and the number of petrochemical workers in relation to the total workforce in each of the studied countries gives an indication of the industry's role in each country's political economy. Although the share of workers employed in the petrochemical industry represents a relatively small share of the total workforce in all the studied countries (Fig. 8), the absolute size of the workforce involved in this industry in countries such as China (3.5 million), the United States (504000), Japan (358000), India (321000) and Russia (240000) hints to the challenges involved in ensuring a just transition and the opposition that will confront plans to transition, unless legitimate concerns and needs among workers are met.

4.2.3. The socio-political landscape

4.2.3.1. Climate policy. Table 4 summarises the net-zero pledges and emission reduction targets (including legal status) of the countries within the scope of this study. Although all countries (except Iran) have committed to net-zero emission targets, only three countries (South Korea, Japan and Germany) have committed to these targets through formal legislation. Half of the countries (the US, South Korea, Japan, Russia and Germany) have put forward interim targets (for 2030) that would result in absolute emission reductions. Both China and India have committed to relative emissions reductions (i.e. reductions in tCO_2/GDP) up to the year 2030. Saudi Arabia, Iran and Taiwan have not yet committed to any meaningful interim targets.

In its evaluation of governmental targets and actions to reduce GHG emissions, Climate Analytics and NewClimate Institute [104] rate governmental climate action on a scale with five ratings: critically insufficient, highly insufficient, insufficient, almost sufficient and 1.5°C Paris Agreement compatible. Of the countries that are part of the scope of this study, two countries (India and Germany) are deemed to have government targets and actions in place that are almost sufficient. In four of the countries (China, the United States, Saudi Arabia and Japan) the ambition level is considered to be insufficient. In South Korea and Russia, the policies enforced so far are considered to be highly insufficient, and policies and action in Iran are deemed to be critically insufficient.

Recognition of carbon pricing instruments as important tools in the climate mitigation toolbox has gradually grown and, in 2021, 21.5 % of global GHG emissions were covered by carbon-pricing instruments in operation. Germany (via the EU Emission Trading Scheme), China (since 2021), South Korea and a few states in the United States now have GHG emission trading systems in place [105]. In both the EU and South Korea, the emissions trading systems cover the industry sector, including the petrochemical industry. China has announced plans to include several industry subsectors. However, most of the countries covered in this study have no carbon-pricing instruments in place.

Table 4
Data on country-level climate targets (including legal status) and net-zero pledges.

	Net-zero pledge	Target year	Status	Interim target 2030 (absolute/ relative)
China	Carbon neutral (ity)	2060	In policy document	Relative
USA	Net zero	2050	In policy document	Absolute
India	Net zero	2070	Declaration	Relative
South Korea	Net zero	2050	In law	Absolute
Saudi Arabia	Net zero	2060	Declaration	Other
Japan	Net zero	2050	In law	Absolute
Russia	Carbon neutral (ity)	2060	Declaration/pledge	Absolute
Iran	–			Other
Germany	Climate neutral	2045	In law	Absolute
Taiwan		2050	Climate Change Response Act with net-zero emissions target (2050) processed	

(Based on data from Refs. [103, 104])

4.2.3.2. Civil liberties, labour rights and social protection. Table 5 summarises the scores for each of the studied countries, which indicate the extent to which political rights, civil liberties and labour rights are recognised in law and in practice. According to Freedom House's [107] evaluation, only half of the countries (the United States, South Korea, Japan, Germany and Taiwan) can be considered 'free'. India is considered to be 'partly free', while the remaining countries have regimes that do not respect political rights or civil liberties in any meaningful way. Saudi Arabia and China are two of the 16 countries across the world with the worst aggregate scores for political rights and civil liberties.

The Labour Rights Indicators [110] give an indication of the extent to which labour rights (including e.g., the right of workers to establish and join organisations, the right to collective bargaining and the right to strike) are respected. As can been seen in the compilation, the access to or denial of labour rights often goes hand-in-hand with access to or the denial of political freedom and civil liberties. In countries such as the United States, Japan and Germany, labour rights, political freedom and civil liberties are largely respected, in both law and practice. Citizens of China and Saudi Arabia, however, are more or less completely denied labour rights, political freedom and civil liberties. In this context, South Korea and Russia are outliers. In South Korea, which is considered to be politically free overall, labour rights are relatively restricted. In Russia, this situation is reversed. Russia does not respect political and civil liberties, but its labour rights tend to be recognised in both law and practice.

Similar patterns can be seen regarding the provision of social protection – that is, countries that respect civil liberties and labour rights tend to provide more encompassing social protection to its citizens. This is true for countries such as the United States, Japan and Germany, which have relatively high expenditures on social protection. As a reference, the total expenditure on social protection (excluding health) in the world is 12.9 % of the GDP on average; however, expenditures vary significantly, ranging from 1.1 % of the GDP in low-income countries to 16.4 in high-income countries.

Table 5
Overview of indicators assessing the extent to which political rights, civil liberties [107] and labour rights [109] are acknowledged and access to social protection is provided [111] in individual countries.

	Global freedom score	Labour rights Normalised score (0 = best, 10 = worst)		Expenditure on social protection (percent of GDP)
		In law	In practice	
China	9/100 (not free)	10.00	10.00	7
USA	83/100 (free)	4.58	0.31	19
India	66/100 (partly free)	6.65	3.60	1
South Korea	83/100 (free)	5.93	5.70	6
Saudi Arabia	7/100 (not free)	10.00	10.00	5
Japan	96/100 (free)	2.07	0.27	16
Russia	19/100 (not free)	4.43	2.08	13
Iran	14/100 (not free)	10.00	10.00	10
Germany	94/100 (free)	0.93	0.59	19
Taiwan	94/100 (free)	n/a	n/a	4

4.2.3.3. Implications for change and a just transition. Only two of the countries within the scope of this study – namely, India and Germany – have climate policies in place that are somewhat near being aligned with the targets set out in the Paris Agreement. Although this study did not carry out a mapping of policies specifically targeting the petrochemical industry, the current level of national ambition in all the studied countries seems to be insufficient to drive change in the petrochemical industry. The second category of indicators shows the extent to which civil liberties and labour rights are respected and the level of social protection within each of the studied countries. With the exception of high-income countries such as the United States, Japan and Germany, the potential for civil society actors to advocate for change and the societal preparedness to handle the socio-economic stresses involved in structural change look bleak.

5. Concluding discussion

Reversing the current trend of increased investments in fossil-fuel-based petrochemical production capacity and transitioning – on a global scale – to more sustainable practices will be a monumental challenge. The aim of this study was to explore the prerequisites for the changes that are needed to address this challenge. We achieved this aim by combining an overview of global and regional trends in the petrochemical industry with a more in-depth mapping and exploration of the prerequisites for change, with a focus on the 10 countries that are currently home to more than 70 % of the operational petrochemical capacity.

This study is an early attempt to contribute to a better understanding of how the preconditions for change and the potential for achieving a just transition vary across some of the countries that are central to the global petrochemical production chain and thus key to escaping the current fossil-fuel lock-in. This knowledge can contribute to a better understanding of the possibility and direction of change in the petrochemical industry, both globally and on a country level. Although this study is limited in scope and depth and in terms of the number of indicators assessed, we believe that it confirms the importance of recognising national and local contexts when planning for and assessing the impacts of industrial change. By exploring the space between previous macro-level studies on transitioning the petrochemical industry and detailed case studies on specific regions and communities closely tied to the industry, this study sheds new light on the challenges involved in devising adequate policy responses, building legitimacy for change and potentially building a bottom-up pressure for a timely climate transition. The assessment shows that taking on these challenges will look very different in oil-and-gas-dependant economies such as Saudi Arabia, Russia and Iran; in countries such as China and India, where there is a large potential/risk for growth in the demand for petrochemical products; and in countries such as Germany and Japan, which have limited access to oil and gas, reasonably ambitious climate policies and reasonably well-developed social safety nets.

More research is definitively warranted to develop adequate policy responses and transition strategies that could contribute to accelerating the change process while handling the wider social and economic stresses. For example, such research could include a widened and deepened country-level analysis complementing the present analysis, with a broader set of indicators (describing e.g. RD&D spending, oil & gas rents, demand-side indicators, green investments and ownership structure). Since many related challenges are evolving across countries and regions, more in-depth case studies would also be valuable, both empirical and comparative, with a focus on the regions and communities most directly affected by the petrochemical industry's sustainability transition.

Efforts to restructure the petrochemical industry and 'turn the tanker' will require facing political resistance and institutional challenges at multiple levels. The necessary transition process will not unfold without concerted action from governments, businesses and civil society actors on the global, national, regional and local levels. Although we are only able to scratch the surface here, the indicators used to explore the prerequisites for change all point to areas in which actions and policies need to advance. As outlined in more depth by Bauer et al. [122], these actions and policies include efforts to hinder the future exploration and expansion of oil and gas, in order to restrain access to fossil feedstocks for petrochemicals and restrict the expansion of fossil-based production capacity. They also include measures to facilitate a shift to renewable feedstocks – where applicable – and to limit and ultimately reduce demand for petrochemical end-use products in general and plastics and fertilisers in particular. The results also underscore the importance of policies and strategies to handle legitimate concerns and needs among workers and frontline communities who are heavily affected by existing unsustainable practices and will face the most direct impacts during a transition. Steps in this direction have been taken in, for example, the U.S. Inflation Reduction act and the EU Just Transition Mechanism. Further, to have a realistic chance of achieving a timely climate transition of the global petrochemical industry, mechanisms must be in place to handle the socio-economic stresses involved in structural change also in countries with fewer resources available, including through international climate financing and technological transfers.

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

Data will be made available on request.

Acknowledgement

The authors would like to thank Linn Brolin, Ylva Kloo and Nora Räthzel for their thoughtful comments on an earlier version of the manuscript. Our gratitude also goes to Fredic Bauer and the rest of the researchers in the Petrochemicals and Climate Change Governance project for inviting us. The research was supported by funding from the V. Kann Rasmussen Foundation.

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