Development transitions for fossil fuel-producing low and lower-middle income countries in a carbon-constrained world

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Abstract

The production and use of fossil fuels need to decline rapidly to limit global warming. While global net-zero scenarios abound, the associated development ramifications for fossil fuel-producing low and lower-middle income countries (LLMICs), as well as adequate international responses, have been underexplored. Here, we conceptualise that depending on country context, three kinds of development transitions follow from declining fossil fuel production and use for LLMIC producers, namely an energy transition, an economic transition and an equitable fossil fuel production transition. We propose a classification of these transitions, arguing that heterogeneity in LLMICs' fossil fuel production and usage significantly impact their pathways towards low-carbon development. We illustrate this by discussing different cases of fossil fuel-producing LLMICs, focusing on Mozambique, India, Lao PDR and Angola. We conclude by detailing context-specific international support portfolios to foster low-carbon development in fossil fuel-producing LLMICs, and call for a re-orientation of international support along principles of global solidarity.

Main

A rapid decline of fossil fuel production and use is required to limit global warming to 1.5 degree[1], a target which may not be reached even if the goals of the Paris Agreement are fulfilled. A 3% decline per year until 2050 in global oil and gas production (and even more in coal[2]) is needed, creating a carbon constraint for the global economy. The International Energy Agency (IEA)'s net-zero scenario projects that there can be no approvals for new oil and gas fields starting from 2021[3]. The Glasgow Climate Pact adopted at COP26 calls for a "phasedown of unabated coal power"[4] (while this terminology is debated, including among the authors of this paper, it is clear that achieving net-zero means ending all unabated fossil fuel production and use). However, the global debate has obscured the complexities involved at the country-level. Due to their high fossil fuel production shares[5], efforts for transitioning away from fossil fuel production have focused on upper-middle income and high income countries

countries[6]. The Beyond Oil and Gas Alliance formed at COP26 does not include any fossil fuel-producing low and lower-middle income country (LLMIC), early movers on implementing related production restrictions instead include Denmark, France, the US, Canada and New Zealand[6].

Yet while upper-middle income and high-income countries are key for global decarbonisation efforts, potential development implications of declining fossil fuel revenues are likely to be most severe for fossil fuel-producing LLMICs due to limited public resources, high reliance on fossil fuel rents for GDP and current development trajectories due to less diversified economies[7]. The United Nations Agenda 2030 on sustainable development repeatedly points towards the need for tailoring development solutions towards developing countries specifically[8], commonly defined according to different per capita income levels[7]. The conundrum of how fossil fuel-producing LLMICs should develop as their fossil fuel revenue streams decline has remained largely unresolved[9], manifested by the following three key issues:

First, the United Nations Framework Convention on Climate Change (UNFCCC) negotiations, think tanks as well as the academic literature often treat fossil fuel-producing LLMICs, and LLMICs in general, as an aggregated group[6,10,11]. However, emerging and more nuanced views[12] suggest substantial country-specific differences in the size, socio-economic importance, and future growth aspirations of fossil fuel production. These differences are likely to have substantial consequences for the set of meaningful future development pathways available to these countries[11].

Second, there is considerable uncertainty regarding how these different historical trajectories affect future development and transition pathways for fossil fuel-producing LLMICs in a carbon-constrained world[9,11]. Scaling renewables and ensuring the transitions are just from a socio-economic perspective will probably be crucial components of these pathways[13]. However, the literature appears to lack a comprehensive and context-specific framework of development and transition strategies for fossil fuel-producing LLMICs.

Third, there is a lack of analyses on how developed countries should support these alternative development pathways[9,13,14]: Existing climate finance mechanisms have failed to materialise at the required level, and, crucially, have not fully considered critical needs of fossil fuel-producing LLMICs regarding their transition pathways to achieve sustainable economic as well as social development in the context of global fossil fuel reduction[9,13,14], in accordance with the United Nations Agenda 2030[8]. As a result, LLMICs have become sceptical regarding the pledges made in climate negotiations, and have increasingly moved towards decision-making based on short-term priorities that are likely to lock them deeper into fossil-based trajectories[11].

In this Perspective, we address these three issues in turn. With respect to the first issue stated above, the subsequent section illustrates the substantive differences between fossil fuel-producing countries. Second, while many different ways of advancing development are crucial in general for LLMICs, we conceptualise three context-specific development transitions which are particularly salient in the context of LMICs reducing their dependence on fossil fuel production and usage. These are an energy transition, an economic transition and an equitable fossil fuel transition. We then chart all fossil fuel-producing LLMICs by fossil fuel production and usage, and illustrate our conceptualisation by discussing salient transition needs and potential development roadmaps for the cases of Lao PDR, Mozambique, India and Angola by building on the literature as well as on the domain knowledge of our co-authors from these countries. Finally, addressing the third issue raised above, we discuss options for support portfolios by developed countries and international finance mechanisms based on assessing countries' readiness for the required transition pathways to enable low-carbon development of fossil fuel-producing LLMICs.

Divergent fossil fuel producer landscape

The 119 fossil fuel-producing countries globally differ markedly in terms of production volume and growth, economic dependency on fossil fuels, location of fuel usage, and domestic versus export orientation of fossil fuel production (Figure 1). Mapping current income levels to these production profiles highlights country-specific divergences with regards to aligning their development and climate goals. These divergences point to considerable socio-economic differences across different country-level income groups in the context of historic interdependences between national income, reliance on fossil fuel rents in terms of their GDP share (depicted by the different bubble sizes), and broader national development. Three of the top ten producers are LLMICs, namely Iran, Indonesia and India. Some comparably large fossil fuel-producing LLMICs (like Iran, Iraq, Libya and Angola), as well as several smaller producers (such as Republic of Congo and Timor-Leste), exhibit substantial economic dependence on fossil fuel extraction, with fossil fuel rents ranging between 24-37% of GDP. Other fossil fuel-producing LLMICs (including Lao PDR, Ghana, Papua New Guinea, Mozambique and Mongolia) have rapidly expanded their respective production in the last decade, exhibiting annual growth rates of 7%-31%. Another category of LLMICs (including Chad, Philippines and Bangladesh) present neither high production volumes nor high dependency on fossil fuels.

[Insert Figure 1 here]

Country-level development transition pathways

The variety of fossil fuel producers underscores the importance of different, country-specific pathways towards development and climate goals. LLMICs can be distinguished along two key factors, namely their export orientation and their planned production growth. This differentiation leads to a conceptual four-way classification framework highlighting the nature of development transitions needed to support development (Figure 2a). The motivation behind this is to point to the context-specificity of associated sustainable development pathways and to inform international support strategies towards LLMIC fossil fuel producers. Specifically, we identify three generic country-level transitions:

First, an **energy transition** means transitioning towards an energy system able to meet a country's economic and social energy needs by replacing fossil fuel shares with low-carbon energy sources[11].

Second, an **economic transition** means transitioning towards a diversified economy based on an expanded set of low-carbon goods and/or services which replace a planned or existing economic dependence on fossil fuel exports[16].

Third, an **equitable fossil fuel production transition** means transitioning away from existing fossil fuel production such that neither affected individuals nor particular subnational regions are left behind socio-economically[14].

While all fossil fuel-producing LLMICs require economically, socially and environmentally sustainable development pathways transitioning from their different degrees of reliance on fossil fuels, our conceptual framework suggests that their current fossil fuel production and usage profile helps to identify which types of transitions are likely to be specifically relevant going forward (see Figure 2a). Crucially, we focus on types of transitions which are likely to be more salient across countries compared to actual end points of these transitions, which especially in terms of the economic system are highly context-dependent. Charting all fossil fuel-producing LLMICs according to their fossil fuel production status and usage suggests a diverse set of current states of dependency on fossil fuels (Figure 2b). Below, we discuss four country cases falling into one of the four conceptual buckets (Lao PDR, Mozambique, India and Angola), illustrating similarities and differences in required transition pathways. The intention is not to extrapolate these individual country experiences to the greater sample, but showcase how our framework can help to identify critical types of transition pathways and point towards transition-specific support needs.

[Insert Figure 2 here]

Emerging domestic producers like Lao PDR plan to extract less fossil fuel than they consume domestically (Figure 2b). An **energy transition** is their most salient transition need. as current economic or social dependence on fossil fuel-production is limited for these countries. High renewable energy endowments in many LLMICs imply the potential to deliver energy security at lower cost than fossil fuels, especially for electricity[22], but considerable challenges often remain. Despite large hydropower resources, Lao PDR has suffered from domestic energy shortages since reservoir storage capacity required to balance seasonal rainfall swings is tied-up in export contracts. In response, Lao PDR has recently focused on unabated domestic coal projects, with 1.8 GW developed to date and a further 5.4 GW in the National Plan[23]. Yet, Lao PDR also has potential alternative routes to energy security via renewables. One approach would be to adjust export agreements and increase the domestic share of Lao PDR's reservoir-backed plants (such as Nam Theun 2). Further, synchronizing hydropower operation to integrate volatile new solar and wind generation greatly reduces emissions, and has been shown to minimize electricity cost, for instance in the case of Ethiopia[24]. This strategy can further support rapid scale-up of capacity: Vietnam installed 6 GW of solar in a single month[25] while new large-scale coal projects in South Africa are still not fully operational after more than 15 years of construction[11]. Moreover, renewables avoid adverse health impacts due to local air and water pollution from fossil fuel production. Yet, in the case of Lao PDR, scale-up of renewables for the domestic market is contingent on improving the creditworthiness of the national utility, Electricite Du Laos, which underwrites power purchase contracts. Ultimately, due to climate change affecting rainfall in Lao PDR, and the country's heavy dependence on hydropower, there is a crucial need to diversify energy sources; especially if the country is to keep pace with growing demands for universal energy access.

Emerging net exporters like Mozambique have plans for substantial fossil fuel exports in the future, but do not yet have significant fossil fuel production capacity. Thus, energy transition as well as economic transition become crucial transition trajectories for such countries. Firstly, in terms of **energy transition**, Mozambique stands at a pivotal juncture, as it plans to become a major natural gas exporter, exploiting its 4 trillion cubic metres of reserves discovered in the early 2010s despite its substantial potential for renewables. By contrast, Mozambique has devoted little institutional and financial focus on developing its solar PV generation potential[26]. Only one 40 MW solar PV plant has been installed and comparably little usage of solar off-grid energy has been leveraged, even with very low electrification rate of roughly 30%[7]. Secondly, emerging net exporters face a need for an **economic transition**. Regarding the gas discovery, the government of Mozambique estimates large associated economic and job-creation[11], even though the exploitation of the natural resources has been linked to increased domestic conflict, corruption and economic distortion[26]. The government has been delaying establishing the country's sovereign wealth fund, and, similarly to the experience of other LLMIC cases with low institutional effectiveness and accountability[26], GDP per capita has fallen by over 20% in the years since the gas discoveries[7]. Indeed, parts of Mozambique's current debt finance has been tied to generating new fossil fuel revenues in the future, further complicating economic transition. Such plans stake limited public resources on the risky prospect of selling large amounts of fossil fuels on global markets post 2030 against the backdrop of a global drive for net-zero[27], limited experience in the sector, comparatively high cost of capital[28] and limited empirical evidence that fossil fuel exports deliver widespread benefits to LLMIC populations[11,27]. To lower these risks, economic transition options for Mozambique include growing hydropower exports to the Southern African Power Pool[29] as well as increasing value-addition and volume in existing sectors such as mining of rare minerals, logistics, tourism, financial services and information service export[26]. Expanding aluminium exports in the long-term may be contingent on significant investments in domestic low-carbon heat sources, such as blue hydrogen which includes carbon capture and storage (CCS), green hydrogen and e-fuels, to reduce their particularly high carbon footprint which is depressing their attractiveness on global markets[11].

Existing domestic producers like India already rely heavily on fossil fuels for their domestic energy needs, suggesting energy transition as well as equitable transition as key development pathways. First, in reference to an **energy transition**, India relies on domestic coal for 70% of its power generation, which is seen as supporting its energy security[30]. Yet, growing investor interest in Indian renewable energy suggests there is a potentially lower-cost path to energy security[31]. This has led to one of the most ambitious and largely domestically financed renewable energy support programmes in the world which has produced weighted average levelized costs of $32 and $33 per megawatt-hour for wind and solar PV, respectively, encompassing both auctions and power purchase agreements[32], well below coal[31]. In addition to limited availability of sufficient low-cost capital, convoluted fiscal and financial arrangements enmeshing the sector risk compromising India's energy transition. Both coal and electricity prices are kept artificially low[33], leaving domestic commercial banks with exposed balance sheets, and power distribution utilities with escalating debt burdens. Second, being the largest coal producer after China, an **equitable fossil fuel production transition** is critical to India's pathway. In India, coal production is currently highly concentrated in 13 producing states and generating 2-10% percent of state GDP[34]. While coal mining and all associated indirect jobs account for only 0.6% of employment[34], it is the sole economic activity in certain districts. This requires careful planning and following equitability principles such that areas affected by the transition are adequately rehabilitated and made amenable for new economic activities. Focusing on developing the high solar potential of some of India's coal producing states could create net positive effects on domestic job creation and regional development compared to coal[35], and would avoid pollution-related health risks.

Existing net exporters like Angola are well established fossil fuel producers who face the complexity of needing to combine all three energy, economic and equitable transition pathways. First, in terms of an **energy transition,** Angola is planning to scale renewable energy deployment, focusing on hydropower and, to a smaller degree, solar energy. Yet, electrification of other sectors such as transport has not been a visible priority, and electricity access especially in rural areas remains extremely low at roughly 10%[7], indicating that oil wealth has not translated to wider energy access benefits. An interesting comparison is with Bolivia, where the country's focus on natural gas has been argued to be at odds with the country's constitutional recognition of the protection of Mother Earth[36], and notable progress includes the planned Laguna Colorada geothermal plant which is designed to supply parts of its generation to nearby indigenous communities. Second, an **economic transition** is a salient challenge as fossil fuels account for over 90% of Angola's exports, with plans to further increase oil exports[22]. Economically diversifying is furthermore complicated for Angola due to known resource curse dynamics (demand increase for the local currency which has negative effects on the competitiveness of other exports). However, likely global oil demand decreases[2], implying significant long-term economic and social risks of this strategy, especially where it is unabated[16]. Carbon dioxide removal (CDR) technologies could be used to reduce the net footprint of their fossil fuel exports in the medium term. However, this would require additional capital investments which, depending on CDR technology used, might result in above-average premiums given Angola's relatively high cost of capital[22,28]. Economic transition options for Angola include to export high-value agriculture and fishery products, metals and rare minerals for the global energy transition, as well as transport and tourism services. Angola aims to increase hydropower sales to South Africa, and has also started a pilot-scale hydrogen export project with Germany. In this sense, Angola's access to existing port infrastructure which aids the feasibility of renewable energy-based exports, is a significant advantage over other existing net exporters that are land-locked like Chad, making export onto world markets at scale significantly more difficult. Third, Angola has not yet made noticeable progress in terms of an **equitable fossil fuel production transition** as it is currently not planning to reduce production. While the fossil fuel industry only employs roughly 0.1% of the Angolan workforce, associated economic and social activity is regionally concentrated and needs to be considered in equitable transitions. Finally, despite the overall complexities, combining different transition pathways can bring valuable synergies: For instance, redirecting existing energy export infrastructure and energy sector skills into green hydrogen production may provide a means of simultaneously delivering the transition of the energy sector and the wider economy, while adding local value and creating jobs[11]. Cross-ministerial efforts to integrate energy and development policies are most likely to capture such synergies between different simultaneous transitions[37]. Notably, despite the complexities of all three of these transition pathways, Timor-Leste in September 2023 became the first fossil fuel-producing country to join the bloc of governments advocating for the Fossil Fuel Non-Proliferation Treaty. This move, motivated by the existential threat of climate change for the small island nation, signals Timor-Leste's willingness to embrace the challenge of transitioning away from fossil fuel production.

Country-specific international support

A country's ability to overcome the many transition challenges depends on a wide array of conditions, including natural resource endowments, human and physical capital and quality of governance. For those LLMICs most dependent on fossil fuels, the prerequisites for transition are often wanting (Figure 3). In addition, many LMICs possess critical development needs beyond the transitions outlined above in areas such as health, education and security. The implication is that fossil fuel-producing LLMICs will struggle to overcome the substantial economic and political barriers to rapid fossil fuel production decline in the absence of greatly enhanced and carefully tailored support from developed countries. In particular, it must be acknowledged that the resource curse often responsible for subpar governance practices in fossil fuel-producing countries, will additionally complicate the achievement of the three transition pathways identified[38].

Historically, fossil fuel producers have received significantly lower levels of Official Development Assistance (ODA) – 3.1% of GNI versus 7.3% for non-fossil fuel producers. – This is likely due to perceived lower financial needs and inadequate governance performance highlighting the interdependency between fossil fuel reliance and overseas aid. Going forward, the magnitude and challenges of the different transition pathways they need to pursue is likely to require significant context-specific, reliable and accessible finance and debt relief packages. In addition to financing, such countries also require a combination of sustained technical and institutional capacity building support to enable the transitions. These should ideally incorporate citizen engagement, which is increasingly identified as an important means of improving the socio-economic impact and enhancing the acceptability of energy transition measures, when adequately and meaningfully crafted[39].

In terms of an **energy transition**, many LLMIC producers are endowed with substantial renewable energy resources (Figure 3), illustrated by the above country cases. Moreover, substantial international experience exists on how to successfully support scale-up of renewable energy resources in LMICs. Nevertheless, while some countries have been establishing supportive regulatory frameworks for clean energy (Figure 3), the country cases above suggest that entrenched incentive structures, vested interests, sunk investments and a lack of political and institutional capacity can slow the transition. A common barrier to the energy transition in fossil fuel-producing LLMICs is the presence of substantial subsidies for the production and/or consumption of fossil fuels, which in addition to their adverse fiscal, environmental and social impacts, undermine economic incentives for the adoption of renewable energy. Furthermore, the climate finance literature has highlighted the failure of developed countries to deliver on their US$100 billion cross-border climate finance commitments to developing countries, while noting the difficulty of unambiguously distinguishing between climate finance and broader development assistance[11]. In fact, when domestic climate finance is included, LLMICs (outside of East Asia and Pacific) have captured 25% of the $850 billion global climate finance in 2020[40]. A key obstacle to raising climate finance for capital-intensive renewable energy from the private sector are the high debt and equity risk premia, ranging from 15 to 30% for equity in most cases, reflecting elevated country risk (Figure 3). This underscores the importance of providing risk capital especially in the short term, coupled with longer-term institutional and technical capacity building assistance. Additionally, for existing net exporters like Angola, CCS and CDR may be options to reduce energy sector emissions which would likely require international finance support, for example through climate finance mechanisms[41]. Ultimately, clean energy exports could in part replace fossil fuel revenues. Yet, the wider geographical availability of clean energy resources imply that future energy exports are less likely to be as concentrated in the hands of specific countries as during the fossil fuel era. Furthermore, landlocked countries like Chad or Zimbabwe face additional logistical challenges participating in global trade, of renewable energy sources such as green hydrogen, that need consideration when designing tailored international support schemes.

Regarding an **economic transition**, most fossil fuel-producing LLMICs lack the required enabling conditions, with low human capital endowment, ease of doing business and government effectiveness scores (Figure 3). While economic diversification can raise development prospects and lower risks of asset stranding[16], replacing fossil fuel exploitation is thus likely to be a tall order for many fossil fuel-producing LLMICs who will require support to implement robust and resilient risks management [42], as such approaches do not exist for most LLMICs today. The development finance community should increase economic transition support through initiatives such as infrastructure investments and export subsidies under the Aid for Trade scheme, targeting measures to raise competitiveness, expand and diversify trade, and promote employment via foreign direct investments[43]. It is key to consider that similar political dynamics observed from the resource curse also complicate the achievement of transition.

[Insert Figure 3 here]

In terms of an **equitable fossil fuel production transition**, most existing fossil fuel producers have vulnerable populations given Human Development Index scores below 0.7 and Gini coefficients in excess of 0.40, as well as limited government revenues (typically below 20% of GDP) with which to fund social protection measures (Figure 3). Our cases suggest that while overall social impact of reducing fossil fuel production on employment may be limited in scale, it can have significant impacts for specific sub-national regions. Just and equitable transition mechanisms can help to disentangle political economy lock-ins in ways that avoid displacing transition costs onto low-income regions or communities, and enable development pathways to be guided by equity principles[14]. Multilateral Development Banks have recognised the importance of mitigating associated social impacts, for instance through provision of financial support for coal mine closures[50]. Crucially, a transition towards clean energy has the potential to yield more equitable development outcomes sub-nationally by increasing energy access through solar off-grid systems, reducing local environmental harm, creating more jobs and sharing benefits more widely[11,22]. Technical capacity support is likely to be a key enabler as clean jobs tend to require higher educational attainment, putting a premium on education and reskilling[16].

Crafting an approach to replacing fossil fuels acceptable to all countries depends on coordinated action on national and international levels, including a substantial, comprehensive, accessible and rapid burst of financial and capacity building support targeted towards fossil fuel-producing LLMICs. Recent Just Energy Transition Partnerships (JETPs) signal a growing readiness of developed countries to provide finance and capacity building vehicles fostering integrated energy and equitable transition (and, to a lesser extent, economic transition)[13]. The recent JETP with Senegal indicates an emerging conviction of expanding the recipient base from only coal producers such as Indonesia, South Africa and Vietnam, namely targeting additional quadrants of Figure 2a. However, crucially, for JETPs to be the much-needed step change for climate finance to LLMICs[13], they need to overcome their heavy reliance on debt finance, deliver on promises of private finance mobilisation, build trust and ensure transparency in fund allocation and governance, as well as sufficiently support country-specific needs for economic and equitable transition programmes[13]. As the transitions discussed in this paper require deep structural changes, support programmes must further ensure sustained long-term support.

Further empirical research and analyses are required to assess the effectiveness of different, context-specific transition designs as well as accompanying policy and finance measures. What is clear is that a long-term commitment to principles of global solidarity is key to ease the particularly challenging transition path for fossil fuel-producing LLMICs and offer attractive alternatives to highly risky and short term-oriented fossil fuel production aspirations by LLMICs.

Figure captions

Figure 1: Country-level fossil fuel production versus fossil fuel production compound annual growth rate (CAGR) 2010-20. All fossil fuel-producing countries displayed with production 2019-21avg > 0.25 QBTU. Not all country names displayed for readability. CAGR = Compound annual growth rate, O&G = Oil and gas, LLMIC = Low and lower-middle income country, UMIC = Upper-middle income country, HIC = High-income country, UAE = United Arab Emirates, Congo, Rep. = Republic of the

Congo, QBTU = quadrillion British Thermal Units, GDP = gross domestic product, avg = average. Fossil fuel production (y-Axis) includes production of petroleum (crude oil and natural gas plant liquids), natural gas and coal[7]. Fossil fuel production CAGR (x-Axis) is calculated over a 10-year-period 2010-20 to reflect structural changes in a country's production volume within the last decade. Basing the calculation on 3-year averages for the starting value (2009-11avg) and the end value (2019-21avg) helps to mitigate the impact of non-structural production volume changes on the calculated CAGR, for instance, caused by temporary price fluctuations. Fossil fuel rents (bubble size) include resource rents from oil, natural gas and coal[15]. Countries are classified as "Primary fuel: Coal" if coal production is greater than O&G production for 2019-21avg; and vice versa for O&G. Countries are classified as "Net exporter" based on primary energy production-consumption balance to indicate contribution to global energy and emission balance, meaning if fossil fuels production 2019-21avg > primary energy consumption from fossil fuels 2019-21avg[5].

Figure 2: Development transitions framework for fossil fuel-producing LLMICs in a carbon-constrained world based on their primary fossil fuel use and current versus planned production status (a), and associated mapping of LLMICs (b). All low and lower-middle income countries (LLMICs) are displayed with a GDP 2019-21avg > $1 billion and (Fossil fuel production 2019-21avg + potential production of sites in development and discovered as of 2022) > 0.01 quadrillion British Thermal Units (QBTU). O&G = Oil and gas, LLMIC = Low and lower-middle income country, DR Congo = Democratic Republic of the Congo, Lao PDR = Lao People's Democratic Republic, avg = average. For production status (x-Axis), sites in development and discovered are included to indicate those countries as emerging producers which actively explore fossil fuel sites. For primary fossil use (y-Axis), production values of sites in development are included to indicate fossil fuel production of emerging producers calculated based on site-level data[17]. Production values of discovered sites are excluded due to high uncertainty of realization and timeline. Planned production values for sites in development are calculated using site-level data in the following way. For O&G sites: If available, production design capacity is used. If not available, annual site production is estimated based on reserve volumes with recovery rate by reserve classification (P1 – 100%, P2 – 65%, P3 – 30%)[18] and 20 years of production with constant volume. For coal sites: Sites in development include those that have the status "proposed", "in testing", "in construction", "permitted" in the source data. If available , production is derived from planned site capacity with utilization factor of 0.75 based on Chinese reference values[19]. If not available, annual site production is estimated based on reserve volume with recovery rate of 85% for surface coal and 40% for underground coal[20] and 35 years of production with constant volume[21]. Fossil fuel rents (bubble size) include resource rents from oil, natural gas and coal[15]. Countries are classified as "Primary fuel: Coal" if coal production is greater than O&G production for 2019-21avg; and vice versa for O&G.

Figure 3: Heatmap illustrating the readiness of fossil fuel-producing LLMICs for different transition pathways along a set of indicative metrics. All LLMICs are displayed with GDP 2019-21avg > $1 billion and (Fossil fuel production 2019-21avg + potential production of sites in development) > 0.01 quadrillion British Thermal Units (QBTU). Latest available values are shown. "-" means no data was available. LLMIC = Low and lower-middle income country, UMIC = Upper-middle income country, HIC = High-income country, SWF = Sovereign Wealth Fund, PV = photovoltaic, ODA = Official Development Assistance, Congo, Dem. Rep. = Democratic Republic of the Congo, Rep. = Republic, Lao PDR = Lao People's Democratic Republic, H_2 = hydrogen, RISE = Regulatory Indicators for Sustainable Energy[45], GDP = gross domestic product, avg = average. Darker cell shadings imply higher relative readiness for a given transition pathway. Missing values are coloured white. Cell colour scale flipped for indicators with lowest value being more preferable (Fossil fuel consumption / Total consumption; Equity risk premium; GINI index). Row background colour is indicative of relevance of the transition pathway for the respective country based on the mapping of Figure 2b. Levelized cost of green H_2 draw on different sources and allow only for indicative comparison, as they differ by methodology (for instance renewables considered, estimation years). Countries with high economic complexity find it easier to diversify[16]. The indicators are taken from the following sources: Share of fossil fuel of primary energy consumption[5]; Feasible PV potential of top 10th percentile of land[44]; Wind power density at 100 m of top 10^{th} percentile windiest area[44]; RISE

renewable energy index[45]; Equity risk premium[28]; GINI index[7]; Government expenditure / GDP[46]; ODA / Gross national income[7]; SWF asset value[47]; Fossil fuel rent / GDP[15]; Levelized cost of green H_2 based on collection from +10 sources obtainable upon request; H_2 transport feasibility, # of ports[48]; Human Capital Index[7]; Government effectiveness[7]; Economic complexity index[49]; Ease of doing business[7].

References

1. Achakulwisut, P. *et al.* Global fossil fuel reduction pathways under different climate mitigation strategies and ambitions. *Nat. Commun.* **14**, 5425 (2023).
2. Welsby, D., Price, J., Pye, S. & Ekins, P. Unextractable fossil fuels in a 1.5° C world. *Nature* **597**, 230–234 (2021).
3. Bouckaert, S. *et al.* Net Zero by 2050 - A Roadmap for the Global Energy Sector. (2021).
4. UNFCCC. *Glasgow Climate Pact*. https://unfccc.int/sites/default/files/resource/cma2021_10_add1_adv.pdf (2021).
5. U.S. Energy Information Administration. International Energy Data. https://www.eia.gov/international/data/world (2023).
6. Erickson, P., Lazarus, M. & Piggot, G. Limiting fossil fuel production as the next big step in climate policy. *Nat. Clim. Chang.* **8**, 1037–1043 (2018).
7. The World Bank Group. World Development Indicators. wdi.worldbank.org (2023).
8. UN DESA. Transforming our world: the 2030 Agenda for Sustainable Development. https://sdgs.un.org/2030agenda (2015).
9. Saha, C. K. & Carter, A. V. Phase-out or lock-in fossil fuels? Least developed countries' burning dilemma. *Extr. Ind. Soc.* **11**, 101140 (2022).
10. UNFCCC. Party Groupings. https://unfccc.int/process-and-meetings/parties-non-party-stakeholders/parties/party-groupings (2023).
11. Mulugetta, Y. *et al.* Africa needs context-relevant evidence to shape its clean energy future. *Nat. Energy* **7**, 1015–1022 (2022).
12. SEI, IISD, ODI, E3G & UNEP. *The Production Gap Report: 2020 Special Report.* https://productiongap.org/2020report (2020).
13. Hege, E. *et al. Just energy transitions in the context of Africa-Europe relations*. https://www.iddri.org/sites/default/files/PDF/Publications/Catalogue Iddri/Rapport/Ukama_Synthesis_v02.pdf (2022).
14. Muttitt, G. & Kartha, S. Equity, climate justice and fossil fuel extraction: principles for a managed phase out. *Clim. Policy* **20**, 1024–1042 (2020).
15. The World Bank Group. The Changing Wealth of Nations 2021. https://datacatalog.worldbank.org/search/dataset/0042066 (2022).
16. Andres, P., Mealy, P., Handler, N. & Fankhauser, S. Stranded nations? Transition risks and opportunities towards a clean economy. *Environ. Res. Lett.* **18**, 45004 (2023).
17. Global Energy Monitor. Global Oil and Gas Extraction Tracker. https://globalenergymonitor.org/projects/global-oil-gas-extraction-tracker/ (2023).
18. Muggeridge, A. *et al.* Recovery rates, enhanced oil recovery and technological limits. *Philos. Trans. A. Math. Phys. Eng. Sci.* **372**, (2014).
19. National Bureau of Statistics of China. The Utilization Rate of National Industrial Capacity in the Third Quarter of 2022. http://www.stats.gov.cn/english/PressRelease/202210/t20221025_1889687.html (2022).
20. Committee on Coal Research Technology and Resource Assessments to Inform Energy Policy, Board on Earth Sciences and Resources, Division on Earth and Life Studies & National Research Council. *Coal: Research and Development to Support National Energy Policy*. *Coal: Research and Development to Support National Energy Policy* (National Academies Press, 2007). doi:10.17226/11977.
21. Hauenstein, C. Stranded assets and early closures in global coal mining under 1.5∘C.

Environ. Res. Lett. **18**, 024021 (2023).

22. African Development Bank Group. *African Economic Outlook 2022*. https://www.afdb.org/en/documents/african-economic-outlook-2022 (2022).
23. Lao Ministry of Energy and Mines. *National Power Development Strategy*. (2021).
24. Sterl, S., Fadly, D., Liersch, S., Koch, H. & Thiery, W. Linking solar and wind power in eastern Africa with operation of the Grand Ethiopian Renaissance Dam. *Nat. Energy* **6**, 407–418 (2021).
25. Leader Associates. Scaling up Rooftop Solar in Vietnam – More than 9GW installed in 2020. *pv magazine* https://www.pv-magazine.com/press-releases/scaling-up-rooftop-solar-in-vietnam-more-than-9gw-installed-in-2020/ (2021).
26. Gaventa, J. *The failure of 'gas for development' - Mozambique case study*. https://www.e3g.org/wp-content/uploads/Gas-for-development-Mozambique-case-study-December-2021.pdf (2021).
27. Mercure, J.-F. *et al.* Reframing incentives for climate policy action. *Nat. Energy* **6**, 1133–1143 (2021).
28. Damodaran, A. Country Default Spreads and Risk Premiums. https://pages.stern.nyu.edu/~adamodar/New_Home_Page/datafile/ctryprem.html (2023).
29. Alova, G., Trotter, P. A. & Money, A. A machine-learning approach to predicting Africa's electricity mix based on planned power plants and their chances of success. *Nat. Energy* **6**, 158–166 (2021).
30. Jain, A. K. Energy security is balancing of green thrust, fossil fuels. *Energyworld* https://energy.economictimes.indiatimes.com/news/renewable/energy-security-is-balancing-of-green-thrust-fossil-fuels/94749319 (2022).
31. Sinha, S. Why India is the new hotspot for renewable energy investors. in *World Economic Forum Annual Meeting* (World Economic Forum, 2020).
32. International Renewable Energy Agency. *Renewable Power Generation Costs in 2020*. (2021).
33. Powell, L., Sati, A. & Tomar, V. K. Coal Pricing in India: The high cost of low Prices. *Obs. Res. Found.* **Aug 8**, (2022).
34. Pai, S. & Zerriffi, H. A novel dataset for analysing sub-national socioeconomic developments in the Indian coal industry. *IOP SciNotes* **2**, 14001 (2021).
35. Pai, S., Zerriffi, H., Jewell, J. & Pathak, J. Solar has greater techno-economic resource suitability than wind for replacing coal mining jobs. *Environ. Res. Lett.* **15**, 34065 (2020).
36. Villavicencio-Calzadilla, P. & Mauger, R. Bolivia's energy transition in harmony with nature: Reality or delusion? in *Dilemmas of Energy Transitions in the Global South* (eds. Kumar, A., Höffken, J. & Pols, A.) 55–77 (Routledge, 2021).
37. Trotter, P. A. *et al.* How climate policies can translate to tangible change: Evidence from eleven low-and lower-middle income countries. *J. Clean. Prod.* **346**, 131014 (2022).
38. Sachs, J. D. & Warner, A. M. The curse of natural resources. *Eur. Econ. Rev.* **45**, 827–838 (2001).
39. Marcon Nora, G. A., Alberton, A. & Ayala, D. H. F. Stakeholder theory and actor-network theory: The stakeholder engagement in energy transitions. *Bus. Strateg. Environ.* **32**, 673–685 (2023).
40. Naran, B. *et al.* Global Landscape of Climate Finance: A Decade of Data 2011–2020. *Clim. Policy Initiat.* (2022).

41. International Development Finance Club. *IDFC Green Finance Mapping Report 2021*. https://www.idfc.org/wp-content/uploads/2021/11/idfc-gfm2021-full-report-final.pdf (2021).

42. Bradley, S., Lahn, G. & Pye, S. Carbon Risk and Resilience. *Chatham House, London* (2018).

43. Cadot, O., Fernandes, A., Gourdon, J., Mattoo, A. & De Melo, J. Evaluating Aid for Trade: A Survey of Recent Studies. *World Bank Policy Res. Work. Pap. No. 6742* (2014).

44. The World Bank Group. World Bank global energy data catalogue. https://datacatalog.worldbank.org/home (2023).

45. The World Bank Group. RISE - Regulatory Indicators for Sustainable Energy. https://rise.esmap.org/ (2022).

46. IMF. *Public Finances in Modern History*. https://www.imf.org/external/datamapper/exp@FPP/USA/FRA/JPN/GBR/SWE/ESP/ITA/ZAF/IND (2023).

47. Sovereign Wealth Fund Institute. Sovereign Wealth Fund Rankings. *2022* https://www.swfinstitute.org/fund-rankings/sovereign-wealth-fund.

48. World Port Source. World Ports by Country. http://www.worldportsource.com/countries.php (2023).

49. The Observatory of Economic Complexity (OEC). Economic complexity country ranking. *Economic complexity country ranking* https://oec.world/ (2023).

50. Stanley, M. C. *et al.* Managing Coal Mine Closure: Achieving a Just Transition for All. *World Bank Group, Washingt.* (2018).

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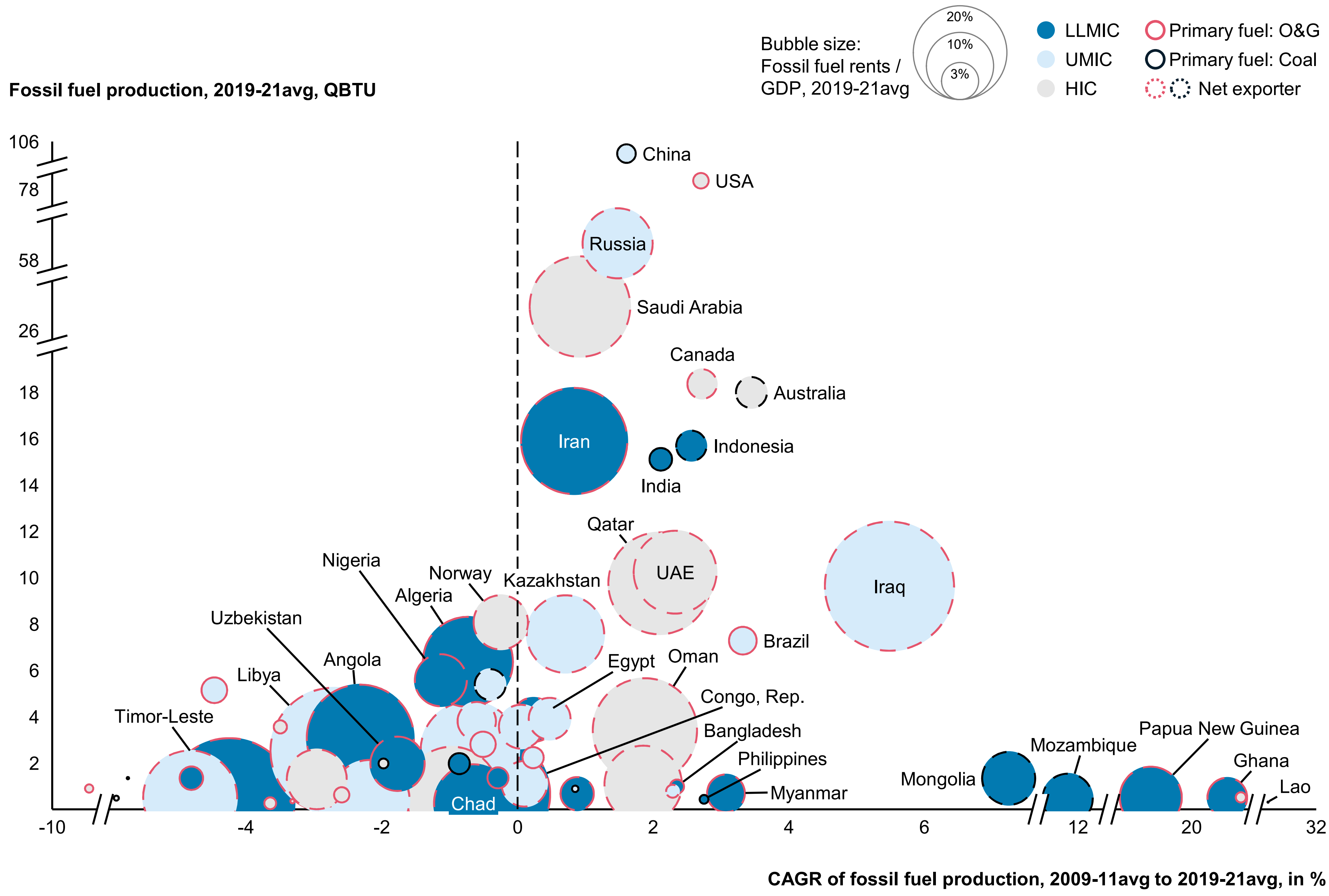
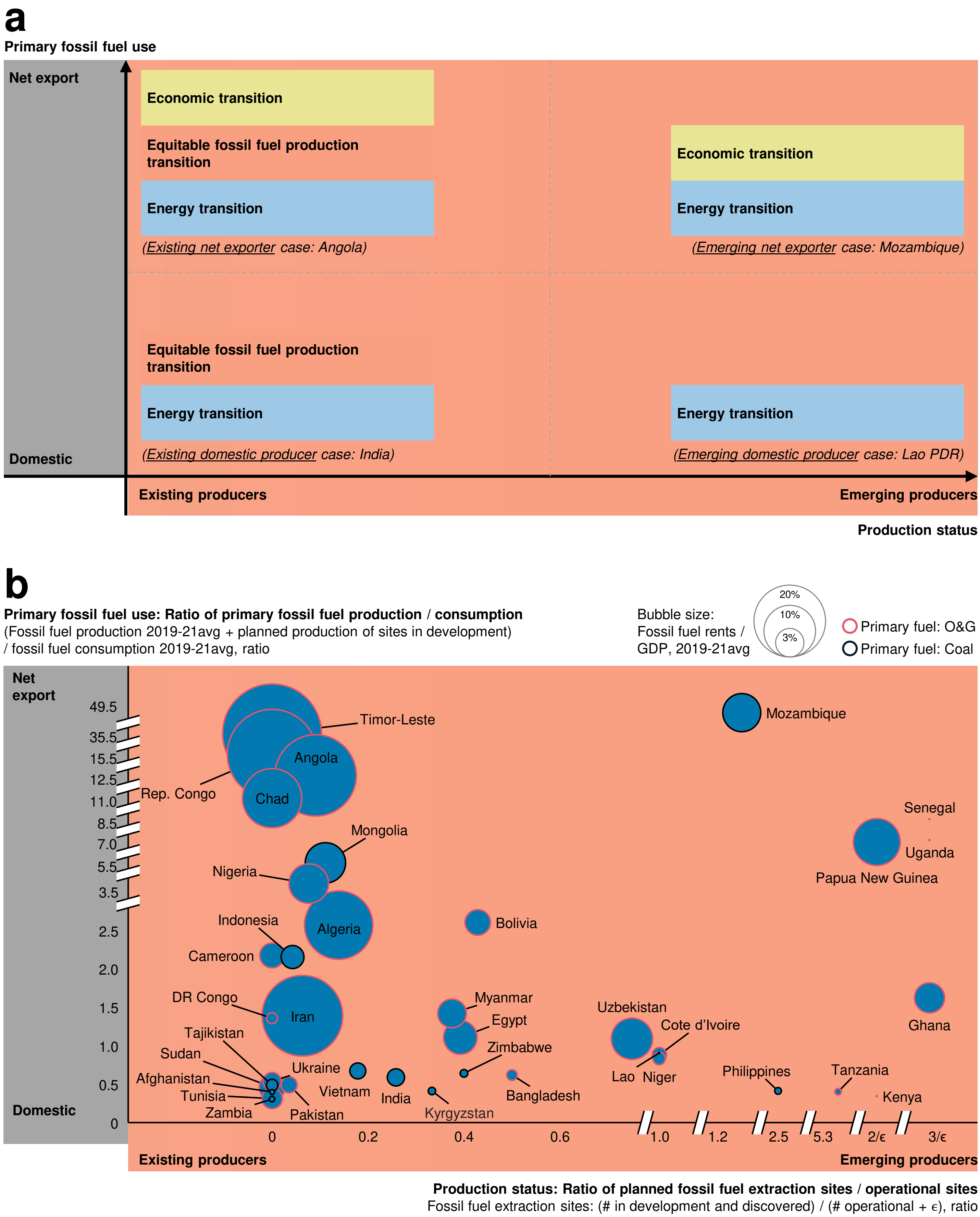
Competing Interests

The authors declare no competing interests.


Fossil fuel production, 2019-21avg, QBTU
Bubble size:
Fossil fuel rents /
GDP, 2019-21avg
20%
10%
3%
LLMIC
UMIC
HIC
Primary fuel: O&G
Primary fuel: Coal
Net exporter
106
78
58
26
18
16
14
12
10
8
6
4
2
-10
-4
-2
0
2
4
6
12
20
32
China
USA
Russia
Saudi Arabia
Canada
Australia
Iran
Indonesia
India
Qatar
UAE
Iraq
Nigeria
Norway
Kazakhstan
Algeria
Uzbekistan
Angola
Libya
Egypt
Oman
Brazil
Congo, Rep.
Timor-Leste
Bangladesh
Philippines
Myanmar
Chad
Mongolia
Mozambique
Papua New Guinea
Ghana
Lao
CAGR of fossil fuel production, 2009-11avg to 2019-21avg, in %


a
Primary fossil fuel use
Net export
Domestic
Economic transition
Equitable fossil fuel production transition
Energy transition
(Existing net exporter case: Angola)
Economic transition
Energy transition
(Emerging net exporter case: Mozambique)
Equitable fossil fuel production transition
Energy transition
(Existing domestic producer case: India)
Energy transition
(Emerging domestic producer case: Lao PDR)
Existing producers
Emerging producers
Production status
b
Primary fossil fuel use: Ratio of primary fossil fuel production / consumption
(Fossil fuel production 2019-21avg + planned production of sites in development)
/ fossil fuel consumption 2019-21avg, ratio
Bubble size:
Fossil fuel rents /
GDP, 2019-21avg
20%
10%
3%
Primary fuel: O&G
Primary fuel: Coal
Net export
Domestic
49.5
35.5
15.5
12.5
11.0
8.5
7.0
5.5
3.5
2.5
2.0
1.5
1.0
0.5
0
Timor-Leste
Angola
Rep. Congo
Chad
Mongolia
Nigeria
Indonesia
Algeria
Cameroon
Bolivia
DR Congo
Iran
Tajikistan
Sudan
Afghanistan
Tunisia
Zambia
Ukraine
Pakistan
Vietnam
India
Kyrgyzstan
Myanmar
Egypt
Zimbabwe
Bangladesh
Uzbekistan
Cote d'Ivoire
Lao
Niger
Philippines
Tanzania
Kenya
Mozambique
Senegal
Uganda
Papua New Guinea
Ghana
0
0.2
0.4
0.6
1.0
1.2
2.5
5.3
2/ϵ
3/ϵ
Existing producers
Emerging producers
Production status: Ratio of planned fossil fuel extraction sites / operational sites
Fossil fuel extraction sites: (# in development and discovered) / (# operational + ϵ), ratio

	Energy transition							Equitable fossil fuel production transition				Economic transition				
	Fossil fuel share of energy use *(%)*	PV potential *(kWh/kWp/d)*	Wind power potential *(W/m^2)*	Levelized cost of green H_2 *($/kg)*	H_2 transport feasibility *(# of ports)*	RISE renewable energy index	Country equity risk premium *(%)*	GINI index	Government expenditure / GDP *(%)*	ODA / Gross national income *(%)*	SWF asset value / GDP *(%)*	Fossil fuel rents / GDP *(%)*	Human capital index	Government effectiveness index	Economic complexity index	Ease of doing business index
Afghanistan	75	5.4	953	-	0	26	-	-	-	32	-	0	0.40	-1.63	-1.20	0.44
Algeria	99	5.2	620	-	18	52	10	0.28	37	0	10	18	0.53	-0.62	-0.88	0.49
Angola	73	5.1	195	5	16	42	15	0.51	19	0	3	26	0.36	-1.06	-1.43	0.41
Bangladesh	98	4.0	167	0	4	37	12	0.32	13	1	-	1	0.46	-0.63	-0.85	0.45
Bolivia	89	6.1	463	-	1	50	16	0.41	34	1	1	3	-	-0.73	-0.97	0.52
Cameroon	69	4.7	197	11	1	34	13	0.47	-	3	-	3	0.40	-0.88	-1.36	0.46
Chad	99	5.2	958	5	0	77	-	0.38	18	6	-	14	0.30	-1.42	-1.93	0.37
Congo, Dem. Rep.	26	4.6	0	5	3	40	15	0.42	-	7	-	1	0.37	-1.72	-1.81	0.36
Congo, Rep.	84	4.0	0	-	4	17	19	0.49	22	2	-	31	0.42	-1.55	-1.02	0.40
Cote d'Ivoire	88	4.4	128	5	4	50	10	0.37	21	2	-	1	0.38	-	-1.19	0.61
Egypt, Arab Rep.	95	5.5	663	6	28	85	15	0.32	-	2	-	5	0.49	-0.43	-0.10	0.60
Ghana	84	4.4	184	5	4	76	23	0.44	26	2	1	4	0.45	-0.15	-1.27	0.60
India	89	4.7	316	6	76	88	8	0.36	30	0	-	1	0.49	0.28	0.61	0.71
Indonesia	94	4.2	144	-	154	53	8	0.38	18	0	0	2	0.54	0.38	0.04	0.70
Iran, Islamic Rep.	98	5.3	744	9	39	82	15	0.41	12	0	-	25	0.59	-0.86	-0.09	0.59
Kenya	72	4.9	687	9	3	65	15	0.41	25	3	-	0	0.55	-0.33	-0.46	0.73
Kyrgyz Republic	45	4.5	880	3	0	34	15	0.29	34	6	-	0	0.60	-0.73	-0.12	0.68
Lao PDR	72	4.1	440	-	0	32	20	0.39	-	3	-	0	0.46	-0.62	-0.70	0.51
Mongolia	95	5.1	730	4	0	21	15	0.33	36	2	-	6	0.61	-0.47	-1.23	0.68
Mozambique	48	4.6	258	5	5	59	19	0.54	-	15	-	6	0.36	-0.77	-1.36	0.55
Myanmar	85	4.3	210	-	5	24	20	0.31	-	2	-	3	0.48	-1.41	-0.85	0.47
Niger	89	5.1	644	4	1	37	15	0.37	24	12	-	1	0.32	-0.61	-0.62	0.57
Nigeria	96	4.7	294	5	12	65	16	0.35	13	1	1	6	0.36	-1.00	-1.56	0.57
Pakistan	84	5.3	606	5	14	42	20	0.30	18	1	-	1	0.41	-0.40	-0.55	0.61
Papua New Guinea	87	4.1	204	-	19	36	13	-	21	5	-	9	0.43	-0.89	-1.84	0.60
Philippines	89	4.2	611	-	68	54	8	0.41	27	0	-	0	0.52	0.07	0.72	0.63
Senegal	93	4.7	260	5	4	60	10	0.38	26	5	3	0	0.42	0.06	-0.59	0.59
Sudan	75	5.2	737	-	3	22	30	0.34	10	11	-	3	0.38	-1.64	-1.33	0.45
Tajikistan	39	5	905	-	0	26	15	0.34	-	5	-	1	0.50	-0.59	-0.69	0.61
Tanzania	86	4.9	340	5	13	50	13	0.41	18	4	-	0	0.39	-0.63	-1.09	0.54
Timor-Leste	100	4.6	414	-	1	-	-	0.29	-	13	467	38	0.45	-0.76	-	0.39
Tunisia	98	5.1	663	3	8	77	19	0.33	33	2	-	2	0.52	-0.17	0.22	0.69
Uganda	68	4.7	149	-	0	66	13	0.43	22	6	-	0	0.38	-0.57	-0.92	0.60
Ukraine	71	3.5	414	-	18	64	23	0.26	40	1	-	1	0.63	-0.41	0.49	0.70
Uzbekistan	97	4.5	634	12	0	35	10	-	31	2	33	7	0.62	-0.20	-0.38	0.70
Vietnam	82	4.1	482	10	15	84	10	0.37	-	0	1	1	0.69	0.28	0.10	0.70
Zambia	42	5.0	233	5	0	59	23	0.57	-	5	-	0	0.40	-0.82	-0.74	0.67
Zimbabwe	74	5.0	266	5	0	53	16	0.50	-	4	-	0	0.47	-1.24	-0.78	0.54

Cell colour code indicates comparison to all countries incl. UMIC and HIC:

75% quantile — *Worst value*

Row background colour indicates relevance of transition pathway based on country's primary fossil fuel use and production (see Figure 2b):

Higher relevance — *Lower relevance*