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Bridging the low-carbon technology gap? Assessing energy initiatives for the Global South

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ABSTRACT

Many developing countries have made their Nationally Determined Contributions (NDCs) conditional on receiving climate finance, technology transfer, and capacity-building support. Due to a lack of engagement from the private sector, countries from the 'Global South' face continued challenges in accessing low-carbon finance and technology. Technology transfer initiatives, including public-private partnerships or intellectual property rights (IPR) sharing platforms, have been suggested to bridge this 'low-carbon technology gap' and promote the technology transfer needed for energy systems transformation. This paper assesses whether such initiatives address the technology gap, as well as other imperatives such as climate justice or carbon lock-in prevention. The paper finds that many low-carbon technology transfer initiatives focus on transferring multiple kinds of technologies to countries that are facing electricity access and governance challenges. Yet these initiatives do not all address the key capacity-building components of knowledge transfer, and countries with poor intellectual property rights (IPR) protections have fewer initiatives on average. Initiatives are also observed less frequently in climate-vulnerable countries. To meet the Paris climate goals, there is an urgent need for the international community to address the low-carbon technology gap by mainstreaming technology transfer into trade and finance.

1. Introduction

The global energy transition is not only aimed at reducing carbon emissions and mitigating climate change, but also improving energy access and affordability, health, gender equality, and sustainable economic growth (Gielen et al., 2019; United Nations Sustainable Development Goals, 2021). The success of countries like China in developing a low-carbon technology sector awakened interest in green growth as a development strategy (Johnson, 2015; Meckling, 2018), and led the International Renewable Energy Agency to frame the energy transition as a way for countries to leapfrog to a more prosperous low-carbon future (IRENA, 2016).

However, falling costs for generation from solar and wind and enabling technologies such as batteries and smart grids are not enough to bring about the global energy transition. Energy investment in Africa, the world's region facing the fiercest energy access challenge, has been low for years (IEA, 2018), and electricity access has worsened since COVID-19 (IEA, 2021). What is more, simply scaling up low-carbon technologies will not necessarily result in 'green industrialization'. For the Global South[1] to achieve the hoped-for development benefits of low-carbon energy, technological solutions need to be embedded in the local environment, which is not always a given (see for example Ockwell et al., 2014). Successful adaptation of technologies depends on the availability of both the technology 'hardware' such as solar panels, and the related 'software', that is the skills and know-how needed to modify technology (Bell, 2012).

China's success in building up a low-carbon technology sector has been credited to the high innovative capacities of Chinese industry (Nahm and Steinfeld, 2014), and policies to encourage knowledge spillovers from international firms such as local content requirements and joint ventures (Lema and Lema, 2012; Gosens and Lu, 2013; Cui et al., 2020). But the success of policies like local content requirements hinge on China leveraging its large and profitable market (Prud'homme et al., 2018) and similar measures have proven to be ineffective or even counter-productive in other countries (Bazilian et al., 2020). This is because creating local production capacities may be costly, and

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[1] We acknowledge that this term is subject to ongoing debate. By Global South we therefore generally denote the non-OECD world.

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industrial policies can discourage foreign investment in developing countries (Pueyo et al., 2012; Johnson, 2015). In other words, there is a fundamental tension between the priorities of governments of developing countries to acquire technology for sustainable development, and technology-holders who seek to maintain their competitive advantage. Countries that enact local content requirements may not see the same success as China, even if their innovative capacities are high – simply because few countries have the kind of market pull needed to attract firms despite potential threats to their competitive advantages.

Against this backdrop, the United Nations Framework Convention on Climate Change (UNFCCC) negotiations saw heated disputes around low-carbon technology access and whether uneven technology ownership disfavors the developing world (Ockwell et al., 2010; Abdel-Latif, 2014; Oh, 2019). As most low-carbon technology patents are held by companies in the Global North, incumbent intellectual property rights (IPR) regimes remain discussed as a potential impediment for the Global South to decarbonize (Zhou, 2019). The majority of National Determined Contributions (NDCs) from developing countries have therefore been made conditional on receiving international finance and technology transfer (Pauw et al., 2019). Yet, the $100 billion per year that developed countries pledged for climate finance has clearly not materialized, and investment in low-carbon energy in countries outside China remains critically insufficient (IEA, 2021). Aggravating the problem, the UN body to promote low-carbon tech transfer (the Climate Technology Centre and Network or CTCN) crucially depends on the finance mechanism for its operations.

Without sufficient international support, many developing countries remain trapped between the short-term imperative to increase energy access with the predominantly fossil-based technologies and finances available to them, and the consequences of climate change (Okereke and Coventry, 2016). This pattern creates the risk of a low-carbon technology gap – that is, a globally uneven distribution of the know-how needed to adapt technologies to the local context and build low-energy systems. Such a gap is not only a serious problem for countries of the Global South, but for the global community in the long term. Energy demand is projected to grow significantly in developing countries in the next decades, in particular on the African continent (IEA, 2021). If these regions become locked in to high-carbon systems, which are very difficult to escape (Unruh and Carrillo-Hermosilla, 2006), this would mean a higher-emissions pathway for the world. In other words, effective clean tech transfer is about avoiding future emissions. In addition, the 'technological divergence' between leaders and laggards in the low-carbon domain (Fagerberg and Srholec, 2017) may come with added risks, as climate and trade become more tightly linked. In the past years, economic blocs like the EU and US have begun considering measures like Border Carbon Adjustment Mechanisms or tariffs (Eicke et al., 2021; Mehling et al., 2019). Moving too slowly on decarbonization may therefore put developing countries in particular at a competitive disadvantage when carbon is priced into their exports (Eicke et al., 2021).

Short of the economic clout of China to 'force' tech transfer via the market, technology transfer initiatives become an important mechanism for developing countries to bridge the technology gap. However, with few key exceptions (De Coninck and Puig, 2015; Ockwell et al., 2014), academic research on low-carbon energy technology transfer as a whole remains focused on the private sector and making receiving countries in the Global South more 'attractive' for tech-carrying foreign direct investment (FDI) (see in Kirchherr and Urban, 2018). What is lacking is an assessment of the initiatives aimed at promoting low-carbon technology transfer and their contribution to bridging the gap. The paper addresses this gap by systematically investigating international initiatives for low-carbon technology transfer. We ask three main questions: what explains the focus, direction, and scope of these initiatives? Do they respond to sustainable development needs, and do they aim to remedy the North-South low-carbon technology gap by targeting those countries least likely to see tech transfer via FDI? And if they respond to other imperatives, what follows from this for policy?

The empirical basis for the assessment is a dataset we compiled on 71 initiatives that transfer low-carbon energy technology,[2] mapping the types of tech transfer and actors involved. The paper then explores whether country characteristics associated with low FDI, signaling the need for alternative mechanisms, are correlated with an increased presence of technology transfer initiatives.

With this, the paper ties into a broader strand of research interested in the mechanisms and politics of technology transfer. Researchers have pointed to a clear potential for transfer of both hardware and know-how to promote local value added (see for example Dai and Xue, 2014; Johnson, 2015; Pueyo et al., 2012), and the Clean Development Mechanism (CDM)'s role in particular (Murphy et al., 2015; Cui et al., 2020; Dechezleprêtre et al., 2008). While the UNFCCC is meant to facilitate technology transfer (Ockwell et al., 2010; Abdel-Latif, 2014), it is also a site of contestation where developed countries' predominantly neoliberal discourse may come to influence policy instruments (Oh, 2019). Other authors have therefore highlighted the importance of South-South cooperation (Kirchherr and Urban, 2018; Urban, 2018), and the potential for new ways of sharing technology beyond the private sector (Pueyo et al., 2012; Ockwell and Byrne, 2015; Morsink et al., 2011, De Coninck and Puig, 2015). Yet so far, comprehensive assessments of public or blended low-carbon technology transfer initiatives are found mainly in the gray literature, and tend to be either focused on evaluating a specific program (Contreras et al., 2018) or are regional in scope (Quitzow et al., 2016). They also do not unpack whether initiatives go beyond transferring the hardware and promote the sharing of 'software', which is a key aspect both from a climate policy and a scholarly viewpoint. Nor do they examine how initiatives are distributed, and how this compares to the commitments the international community has made in the Paris Agreement to close the low-carbon gap between countries. The present paper is, to the best of our knowledge, the first to offer an encompassing and structured assessment of such initiatives. This assessment allows for an empirical exploration of the patterns and 'blind spots' in existing global efforts to support the deployment and transfer of sustainable technology solutions. Because developing country NDCs are conditional on technology transfer (Pauw et al., 2019), it also contributes to understanding roadblocks and potential pitfalls in international climate negotiations.

It is important to note the limitations facing this paper. First, the mapping of initiatives focused on those active during 2019. Therefore, it does not analyze changes over time such as the entry or exit of actors, or an altered geographical distribution. In focusing on comparisons between countries it cannot speak to within-country dynamics, where differences between firms and regions emerge (Bayer and Urpelainen, 2012; Dai et al., 2021). Also, the paper does not evaluate the effectiveness of individual initiatives; it only records whether the preconditions for successful technology transfer (simultaneous transfer of hardware and software) are present. Finally, although the method seeks to capture the most relevant initiatives, the dataset may be limited given various constraints such as language and information available online. Still, the structured assessment yields important insights into the patterns of technology transfer beyond the private sector, and speaks to the debate on technology transfer for reaching developing country NDCs and avoiding carbon lock-in.

With that in mind, the article proceeds as follows. Section 2 summarizes the literature on technology transfer and low-carbon tech and offers a framework for assessing the dimensions of the low-carbon gap that should be addressed by initiatives. Section 3 details the research method, presents the data, maps low-carbon technology transfer

[2] We solely focus on those technologies with the potential to transform whole energy systems; although we acknowledge that other technologies like clean cooking devices address related goals and improve quality of life, our focus in this paper is avoidance of carbon lock-in overall.

initiatives, and explains the results of the statistical tests. Section 4 discusses the findings and argues that while initiatives do have a development focus, they neglect key aspects of global climate justice, offering some implications for the future design of low-carbon technology transfer initiatives. A final section concludes.

2. When and how does technology transfer occur?

This section looks at the literature on technology transfer, and the importance of adopting technologies to local contexts for development and economic value creation. Although involvement in global production networks may result in technology transfer, firms generally aim to protect the technologies that give them competitive advantages. As such, the literature on low-carbon tech transfer is focused on firms and misses the fact that transfer is more likely to be delivered by the international community, which through the UNFCCC has promised to deliver sustainable development and climate justice.

2.1. Technology transfer, diffusion, and development

Technology transfer has been a part of the academic and political debate since the 1970s, and the literature around it is as complex as the process itself. The Intergovernmental Panel on Climate Change (IPCC and Bert Metz, 2000) describes technology transfer as the "diffusion of technologies and technology cooperation across and within countries … the process of learning to understand, utilize and replicate the technology, including the capacity to choose it and adapt it to local conditions and integrate it with indigenous technologies" (pp. 3). This definition points to the important difference between technology diffusion and technology transfer: while diffusion refers to technology use, transfer envisions local adaptation and innovation. Bell (1990) depicts technology transfer as occurring in three streams: the flow of goods and services; the flow of skills and know-how; and the flow of knowledge and expertise. This 'third stream' of expertise is necessary to be able to innovate (Bell, 1990) and is most often neglected (Watson and Byrne, 2012). Whether or not an actor can make use of transferred expertise depends on their absorptive capacity, which Cohen and Levinthal (1990) defined as the ability to "assimilate and replicate new knowledge gained from external sources" (pp. 128).

Technology travels through channels such as FDI, trade, and licensing (Gallagher et al., 2006), and the movement of skilled persons (Pueyo et al., 2012). The globalization of production networks plays a key role, as the relocation of production processes to developing countries enables the possibility of knowledge spillovers – although whether or not 'spillovers' result in technology transfer depends on factors such as local institutional capacities, and the characteristics of the domestic economy and firms (Pipkin and Fuentes, 2017; Dai et al., 2021). Studies have also pointed out ways beyond the market that tech transfer can be promoted, for example through development assistance (Röttgers and Grote, 2014) or technology provisions in trade agreements (Martínez-Zarzoso and Chelala, 2021). While it is beyond the scope of this paper to fully summarize this literature, we take away the key points that a country's participation in global production networks may result in knowledge spillovers for its firms, which can contribute to technology transfer. As multinational firms are the main owners of low-carbon technologies (Pueyo et al., 2012) this raises the question why firms may or may not operate in a given country.

In general, countries with large markets and/or low production costs attract more investment, a function of multinational firms seeking to improve the economics of production or gain access to new markets (Markusen, 2002). Firms are also more likely to invest in a country with internal stability and law and order (Busse and Hefeker, 2007; Asiedu, 2006). Some firms may also prefer to operate in countries with established innovation ecosystems, as this implies lower transaction costs following the relocation of production (Bell, 2012). However, high innovative capacities can also mean the potential for reverse engineering and imitation (Gallagher et al., 2006). Because companies tend to prefer a low risk of imitation when choosing where to do business, countries with high innovative capacity may in fact face constraints in becoming part of global production networks. This is where strong IPR regimes emerge as an important factor for a given country's participation in global production networks, as they mitigate the risk of imitation (Branstetter and Saggi, 2011).

While lead firms aim to expand their markets without losing competitive advantages, other actors such as supplier firms and governments seek to promote tech transfer and ensuing economic and innovation benefits (see for example Pipkin and Fuentes, 2017). Building indigenous industries which are better equipped to adapt and invent technologies is widely seen as the most sustainable strategy, but industry-building through technology transfer using policies like local content requirements is complex. Such mechanisms may be ineffective or even counter-productive if they discourage FDI, which may be the case in countries with relatively small markets, or poor regulatory design and coherence (Johnson, 2015; Bazilian et al., 2020). In addition, such 'forced technology transfer' mechanisms (Prud'homme et al., 2018) may be politically controversial and become subject to international trade disputes, as has also been observed for the clean energy domain between the US and China (Hughes and Meckling, 2017). Lastly, there is a possibility for technology transfer to inhibit domestic innovation, even in countries with high innovative capacity such as China (Howell, 2018).

This throws up another problem: most technologies remain created by and for the 'Global North' and may not respond to the needs of developing countries. Companies have a strong incentive to focus on revenue-generating products, which makes them invest in the development of products that can be sold to Western customers, rather than those that address the needs of people in the Global South (Abbott, 2009). This goes to the heart of justice concerns around both distributive and participatory justice: if market pull determines research investment, the ability to influence the development of new products and solutions is in the hands of those countries with significant buying power (Tvedt, 2010). States have looked at ways to create market pull in other industries, for example through pooling mechanisms aggregating demand (Nemzoff et al., 2019), or tendered procurement (Danzon et al., 2015). Yet the extent to which states can create market pull is limited by capacities and by resources; here, public-private partnerships may play a key role in designing and transferring technologies that can address the needs of the Global South (Abbott, 2018).

While the literature provides insights into the general channels and conditions of technology transfer, we might expect differences in the low-carbon energy technology domain. Not only are there justice concerns with a lack of technology transfer; in addition, the Paris Agreement represents a commitment to help developing countries decarbonize and adapt to climate risks (Zamarioli et al., 2021, McCauley and Heffron, 2018). While acknowledging the importance of other sustainable technologies, we focus on renewable energy and enabling technologies due to their potential to transform energy systems (Gielen et al., 2019). This is what we turn to next.

2.2. Low-carbon energy technology transfer

When it comes to the channels of low-carbon technology transfer, the focus of the literature is on the private sector (see analysis in Kirchherr and Urban, 2018). Much has been written around the role of the CDM, and especially the successes of China in attracting investment (Bayer and Urpelainen, 2012) and building a low-carbon technology sector thanks to a combination of attractive markets, high innovative capacity, and policies to encourage technology transfer (Dai and Xue, 2014; Watson et al., 2015; Chen and Lees, 2016; Cui et al., 2020). China has become highly successful in the manufacturing and innovation of low-carbon technologies (Nahm, 2017) – although some authors argue that at least in the wind energy technology sector, catching-up is limited

(Nordensvard et al., 2018).

In addition, low-carbon technology transfer appears to have followed market size and emissions, passing over other regions. Lema and Lema (2013) and Phillips et al. (2013) demonstrate that technology transfer via the CDM runs along already-established patterns rather than opening new channels. Africa saw comparatively few projects, which authors attribute to the importance of existing trade flows, market size, and human capital (Röttgers and Grote, 2014). While the literature on low-carbon technology transfer often refers to inequalities between North and South or developing countries, it largely focuses on China, India, and Brazil with the exception of some case studies, including on Chile (Pueyo et al., 2011), South Africa (Baker and Sovacool, 2017), Kenya (Byrne et al., 2018), and Botswana and Namibia (Klintenberg et al., 2014). Still, the bias in the literature may in part reflect the geography of global renewable energy investment, which is more present in those countries which are also attractive to FDI generally (Adenle et al., 2017).

Although it is considered useful for absorbing transferred technology, evidence on the role of innovation capacities in attracting private investment and technology transfer remains mixed. Dechezleprêtre et al. (2008) found a positive correlation between high innovation capacities and technology transfer. In contrast, Murphy et al. (2015) observe that CDM technology transfer projects dropped for top recipients after 2007, which they link to recipients having developed sufficient local capacities to no longer need technology transfer. An alternate explanation is that foreign innovators became wary of transferring technology to countries in the Global South with the potential to compete (Bayer and Urpelainen, 2012), which is echoed by the general trend towards pushback against China's green industrialization strategy and trade disputes (Lewis, 2014; McCarthy, 2016; Meckling and Hughes, 2018; Hughes and Meckling, 2017). The relationship between IPRs and technology transfer, a politically sensitive topic at the UNFCCC (Ockwell et al., 2010; Abdel-Latif, 2014; Oh, 2019) remains similarly unclear. In emerging economies, IPRs are indeed one dimension along which foreign firms optimize alongside the business environment (Rai et al., 2014). Yet their role in protecting a firm's competitive advantage may differ also between technologies—IPRs may be more important in science and technology-intensive industries like solar PV than for engineering-based innovation systems for wind (Binz and Truffer, 2017).

There is another possible reason that countries could receive low-carbon technology transfer, beyond the profit motive of the private sector: the international commitments to climate mitigation and climate justice. Indeed, research shows that equity concerns have become part of global climate governance, shaping institutions for technology transfer (McGee and Wenta, 2014). Moreover, it is in the interest of the global community to prevent carbon lock-in in those regions where energy demand is expected to grow in the future, especially the African continent. In addition, there is a threat that the growing awareness of climate risks among investors would result in less private finance for vulnerable countries (Zamarioli et al., 2021). Although the UNFCCC now focuses on equity and common but differentiated responsibility and respective capabilities, Least Developed Countries (LDCs) and Small Island Developing States (SIDS) are meant to be given particular support from developed countries (Okereke and Coventry, 2016). Many countries have made their NDCs conditional on receiving financial and technical support (Pauw et al., 2019), and some particularly climate-vulnerable countries have called for 'climate reparations' from the Global North (Sealey-Huggins, 2017). Practically, this implies that countries that are most vulnerable to climate change and least culpable for current emissions are to be supported by those with higher capacities to do so and higher historical emissions through the international climate regime.

Distributive justice is only part of the picture; beyond the question of who pays, there is also the question of recognition and procedural justice (Jenkins et al., 2016; McCauley and Heffron, 2018; Sovacool et al., 2016). A just energy system is one that equitably distributes costs and benefits, and has fair and representative decision-making processes (Sovacool and Dworkin, 2015). In the current low-carbon technology landscape, the environmental costs of low-carbon energy technologies may indeed be unevenly distributed (Sovacool et al., 2020). Without low-carbon technology transfer, so too are the capacities to be represented and participate in energy systems change. In a system where the development of technologies rests on market pull, the power to influence how new products are developed remains in the Global North. This is also crucial in the context of international contestation around IPR ownership, wherein developing countries have criticized the privatization of technologies and demanded exceptions to IPR protections as well as funding to buy and share technologies (Oh, 2019). Given that technologies that do not meet local needs may also have limited uptake, authors suggest it is crucial to take a collaborative approach to technological change (De Coninck and Puig, 2015).

Research on tech transfer under the UNFCCC has pointed to the neoliberal bias in negotiations and policy design (Oh, 2019), and calls from developing countries for solutions beyond the market to address structural inequalities (Abdel-Latif, 2014; Oh, 2019). Still, academic work has largely focused on FDI and trade. Empirical assessments of public or blended mechanisms remains sparse, although this gap has begun to be addressed in recent years. Forsyth (2007) compares cross-sector partnerships, emphasizing that in some cases such partnerships make investments more effective because local stakeholders accept new technologies. As Morsink et al. (2011) show, multi-stakeholder partnerships can have the potential to prevent disagreements around IPRs and encourage enabling environments. An evaluation of R&D collaborations by Ockwell et al. (2014) finds that while these collaborations have different motivations from the private sector, they remain focused on more profitable areas (that is, mitigation rather than adaptation and emerging economies rather than LDCs). Innovation collaboration also seems to be more intense between OECD countries and those with already higher capacities and environmental standards, thereby excluding many smaller and developing countries (Corrocher and Mancusi, 2021; Verdolini and Bosetti, 2017). A solution proposed by Ockwell and Byrne (2015) to move beyond diffusion to holistic technology transfer is the creation of 'Climate Innovation Centers', which should serve as hubs for such work. Yet a methodical assessment of this patchwork of efforts has not yet been undertaken.

2.3. *Research focus and approach*

As the above discussion suggests, several factors can prevent low-carbon technology transfer despite falling unit costs. Markets may not deliver investment in countries that are 'unattractive', resulting in a lack of FDI; and lead firms are not incentivized to share the knowledge and skills that are the source of their competitive advantages. Smaller developing countries may therefore look beyond the market to the international community, which under the Paris Agreement has committed to delivering low-carbon technology. Here, other channels such as technology transfer partnerships or initiatives may have a role to play in addressing the globally lopsided distribution of knowledge and technological capacity emphasized in developing countries' conditional NDCs.

This raises two questions for the present investigation. First, what is the focus and scope of technology transfer initiatives? Second, in which countries do technology transfer initiatives operate, and what can this tell us about whether initiatives begin to address the global technology gap?

The first question is addressed with a thorough, descriptive mapping of low-carbon technology transfer initiatives including whether they aim to transfer knowledge and expertise, the actors involved, and the kinds of technologies they transfer. The second question is explored using regression analysis, testing whether there are correlations between the number of initiatives operating in a country and variables indicating its vulnerability to the low-carbon technology gap.

Our expectations flow from the preceding discussion on technology transfer via production networks, stating that companies are less likely to operate and invest in certain locations which are 'unattractive' to investors: those with low market pull, low stability, less stringent property rights protections and the potential for reverse engineering. Given international commitments to transfer technology, we expect that where private actors fall short, international low-carbon technology transfer initiatives should step in to bridge the (technology) gap. More specifically, we posit the following hypotheses:

H1. Demand pull: Countries with small electricity markets will be the recipients of more technology transfer initiatives.

H2. Political stability: Politically unstable countries will be the recipients of more technology transfer initiatives.

H3. Intellectual property rights: Countries with poor legal IP protections will be the recipients of more technology transfer initiatives.

H4. Capabilities: Countries with higher potential for reverse engineering will be the recipients of more technology transfer initiatives.

In addition, we expect that the international consensus on supporting climate-vulnerable countries will result in more initiatives in countries with a high climate risk, especially if investors are aware of these risks and avoid such contexts as well. This results in the hypothesis that:

H5. Countries that are most vulnerable to climate change will be the recipients of more technology transfer initiatives.

Lastly, we posit that an important goal of low-carbon technology transfer initiatives may be to prevent carbon lock-in. The imperative to provide low-cost energy for growing populations is named as a key reason that investments in fossil fuels continue (Okereke and Coventry, 2016); once infrastructure centered on fossil fuels is established, it is very difficult to change pathways (Unruh and Carrillo-Hermosilla, 2006). Moreover, technology transfer is explicitly named by developing countries in their NDCs as a way to sustainably meet energy needs (Pauw et al., 2019). This focus on development differs from previous market mechanisms such as the CDM, where the primary goal was to lower global emissions as cheaply and quickly as possible. Therefore, we expect that initiatives will not go to the countries with the most carbon-intensive energy systems. Instead, they should target those countries where future emissions will rise. Our final hypothesis is:

H6. Carbon lock-in: Countries with higher future (and presently comparably low) CO2 emissions will be the recipients of more technology transfer initiatives.

At this point, it is important to define low-carbon energy technologies as those technologies that generate renewable energy and enable their use. Technologies that reduce emissions but do not result in energy systems change are not included, such as gas, hybrid vehicles, or carbon capture. Moreover, while acknowledging that South-South and South-North transfer and innovation are undergoing crucial growth (Urban, 2018; Mallett, 2015), the focus of the present study is not exclusively on such initiatives. Due to the North-South imbalances of low-carbon energy finance and technology ownership, the climate justice imperative of historical responsibility and risk exposure, and the fact that many developing countries have made their NDCs conditional on technology and financial support, we are focused on initiatives that engage in technology transfer with non-OECD countries.

3. Methodology and research strategy

We assess low-carbon technology transfer initiatives in three steps: mapping and investigation of initiatives, creating a dataset, and modeling relationships of tech transfer gap characteristics to coverage. Here, first patterns emerge: international efforts to address the low-carbon gap largely take the form of public-private partnerships and focus on building up clean energy systems by promoting different kinds of technologies. However, not all initiatives aim to transfer hardware and software at once, and some countries see more initiatives than others. We therefore explore whether the presence of initiatives in a country correlates with vulnerability to the technology gap, carbon lock-in, and climate risk.

3.1. Mapping and classifying low-carbon technology transfer initiatives

For the empirical investigation, we compiled a database on technology transfer initiatives. Data were collected on initiatives beginning with the identification of key low-carbon technology transfer actors. These are understood as agents and organizations that are instrumental in facilitating or implementing tech transfer. They were selected only based on their role as transfer agents, without regard to type of actors (private, public, etc.). The first step was an extensive literature review involving both academic works on energy technology transfer, and a substantive body of the gray literature, including papers on specific types of initiatives such as patent pledges (Awad, 2015; Contreras et al., 2018) and technology partnerships (Lewis, 2015; Ghosh et al., 2015), as well as mapping reports (Quitzow et al., 2016; Hultman et al., 2012). This literature review was cross-checked with the websites of relevant development banks and NGOs involved in initiatives, as well as the website of the UN Climate Technology Centre and Network. Building outwards from these key actors allowed us to identify further partners and cross-check their websites for relevant actors, and further initiatives.

Next, we collected detailed data on the operations and goals of each initiative from pertinent websites and reports. This was complemented by email correspondence and targeted surveys of these organizations' representatives, who were asked to provide further information on their work, as well as contribute to the snowballing technique by identifying further actors and initiatives working on technology transfer. Communication and desktop research were conducted in English, French, and German; other languages were automatically translated. Given our focus on the role of technology transfer for development and support of conditional NDCs, we focused on initiatives that had one or more partners in a non-OECD region. We excluded initiatives without active and operational technology transfer, e.g., 'alliances' without an action component, or 'green funds' where technology transfer is not an objective. In addition, initiatives that worked simultaneously on fossil energy were excluded from the sample, as such projects can contribute to pathways of carbon lock-in (Unruh and Carrillo-Hermosilla, 2006).[3]

The resulting database includes detailed information on 71 low-carbon technology transfer initiatives: the technology being transferred, locations of operation, and types of actors in the initiative (characterized as public-private partnerships, private sector, development banks, or multilateral government initiatives). Moreover, we coded the initiatives according to 'stream' of technology transfer as per Bell's typology: the transfer of goods, transfer of skills and know-how, and transfer of knowledge. This categorization was based on the information available online and surveys of representatives.

The data provide an overall picture of which low-carbon technologies are being transferred and by whom. Existing technology transfer initiatives are dominated by public-private partnerships, which made up around two-thirds of the total. Development banks also play an important role, and multilateral government initiatives make up the rest of the selection. Within these different classifications there is a large degree of difference; especially public-private partnerships may vary in their internal governance structures. Although IPR-sharing initiatives and public R&D cooperation were identified by the literature as having important potential (Lewis, 2015; Ockwell et al., 2014), they were not observed in the mapping. At the time of data collection, public R&D partnerships such as the US-India Joint Centre for Building Energy

[3] See Appendix for the list of initiatives, as well as further information on research processes and survey.

Research and Development were inactive. Initiatives that focused on IPR-sharing such as the EcoPatent Commons and GreenXChange were defunct, and no new initiatives were identified.

Furthermore, we find that initiatives aim to transfer different types of technologies: renewable energy generation (solar, wind, geothermal, biomass and small hydro), enabling technologies (storage and grids), and other low-carbon energy (nuclear power, hydropower, energy efficiency). Most initiatives transfer all three types of low-carbon technologies. While no initiatives target only enabling technologies, most include them, and 20 percent of initiatives include both generation and enabling technologies. This suggests that the focus of initiatives is not only delivering the cheapest energy technologies per kilowatt hour, but rather using multiple technologies to build resilient energy systems.

As to technology diffusion vs. transfer, approximately a third of all initiatives worked on various 'streams' simultaneously (see Fig. 1). Others provided hardware and some training without an elaborated component to help transfer knowledge by targeted innovative capacity-building, even though the assessed initiatives were selected specifically for their emphasis on transfer rather than diffusion.

The mapping exercise shows that initiatives are indeed aiming to transfer energy 'hardware' around the world, as well as 'software' to a certain extent. Most projects are public-private partnerships, focusing on multiple kinds of technologies for energy systems transformation (generation, transmission, and efficiency were particularly common). It also becomes apparent that initiatives operate more in some countries than others (see Fig. 2): for example, no initiatives were observed in Albania, whereas other countries such as Uganda had up to 20 initiatives in operation.

The second question remains: why do certain countries receive more technology transfer initiatives than others? More specifically, do initiatives follow FDI in focusing on more attractive markets, or do they aim to fill the technology and finance gap? And do they address the needs of developing countries to escape carbon lock-in, and/or target those countries which see the worst climate impacts?

3.2. Testing for country characteristics: the model

Looking for patterns in the distribution of technology transfer, we first measure the number of initiatives operating in a country in 2019. This is done by adding one point for each time an initiative was present in a country, resulting in a count variable for each country. Given that we are interested in countries aiming for low-carbon technology transfer to reach their NDCs, we narrow the selection to exclude UN Annex 1 and OECD countries, which gives us a sample of 128 relevant countries and territories for analysis. Our variable of interest for the analysis is the number of initiatives operating in a given country. The average number of initiatives operating in a country is 5; the minimum is zero, and the maximum observed is 20.

The next steps explore whether initiatives aim to fill a technology

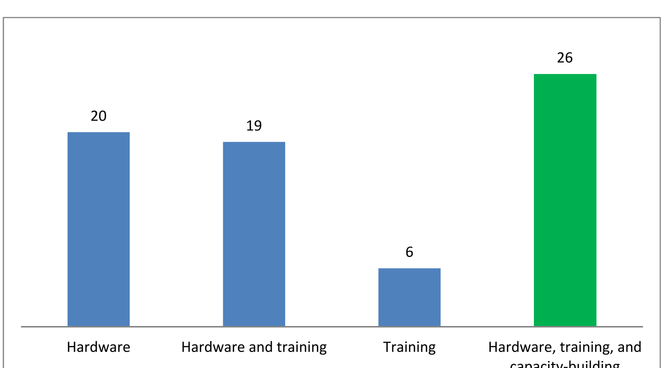

Fig. 1. Low-carbon technology transfer by stream. Source: own data, N = 71.

gap by operating in countries that are usually passed over by the private sector; address climate justice concerns; or prevent carbon lock-in. We test these hypotheses with a negative binomial regression using the boot. stepAIC procedure in R. The dependent variable, the number of initiatives per country, is a count variable. Because our data display overdispersion, a Negative Binomial distribution is the most appropriate model (Zeileis et al., 2008). We use a bootstrap procedure for both model selection and model validation to avoid commonly occurring problems such as multicollinearity, overestimating goodness of fit, and mistaking spurious variables for predictor variables (Austin and Tu, 2004). The explanatory power of variables is determined by their contribution to the Akaike Information Criterion (AIC).

3.2.1. Independent variables

Market size is operationalized as the percent of country population with electricity access (World Bank, 2017), indicating the degree of market maturity and hence market pull. Governance is measured using a country's average score on the World Bank's Worldwide Governance Indicators for 2017 (see Kaufmann et al., 2011). We also measure threats to competitive advantages of the private sector—that is, low property rights protections and high absorptive capacity. We operationalize absorptive capacity as 'Knowledge Absorption' from the Global Innovation Index (see Dutta et al., 2018). The level of intellectual property rights protections is represented by the Intellectual Property Rights sub-index of the Property Rights Alliance (Levy-Carciente, 2017). These measures are not available for all countries: of the 128 countries of interest, data on IPRs and capacity are missing for approximately one third. Nevertheless, these indicators are important to test whether initiatives are seen in locations where there is a risk to competitive advantages of technology holders. We account for the fact that IPR and capacity data tend to be missing for smaller countries by adding GDP to the initial models, and by running separate models on those countries for which this data was missing. Since initiatives may also be more likely to occur in countries where the goal is avoiding carbon lock-in, we measure the CO2 emissions in metric tons per capita (World Bank, 2017). Climate change risks are measured by Germanwatch's Climate Risk Index (CRI), and by the number of fatalities from climate disasters per 100,000 inhabitants (Eckstein et al., 2018). All independent variables refer to the year 2017 or 2016 as this would have been available to decision-makers at the time.

3.2.2. Model selection and validation

The model selection and validation using the bootstepAIC procedure in R (shown in detail in the Appendix) suggests a consistent relationship of number of initiatives per country with electricity access rates, emissions, climate fatalities, IPR protections, and knowledge absorption capacity. As for the role of governance, the bootstep procedure reveals mixed results: better governance scores are positively correlated with the presence of initiatives in the larger sample, but once IPR protections are introduced, this relationship becomes negative. Given that the countries for which we do not have IP data have lower average governance ratings and lower GDP, we repeat the boot.stepAIC procedure on the group of countries for which we do not have information on IPR protections. This gives similar results. There is no relationship between number of initiatives and GDP, nor climate risk as measured by the CRI index. The variables not selected in the boot.stepAIC are therefore excluded for a more parsimonious model (see in Austin and Tu, 2004).

3.2.3. Negative binomial models

Following model selection, we explore in detail how the number of initiatives in a country relates to different dimensions of the low-carbon technology gap (market size, governance, threats to competitive advantages of technology-holders), as well as climate concerns (emissions and risk). The models in Table 1 show the log of the expected count of initiatives as a function of the variables of interest. To interpret the results, all predictor variables except the variable of interest are held

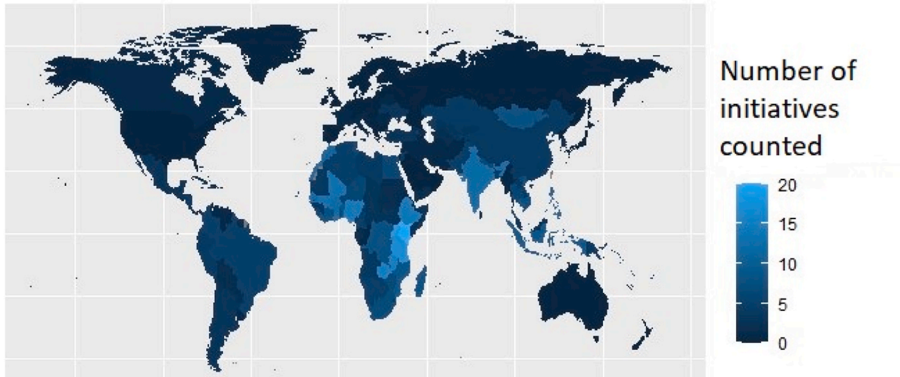

Fig. 2. Number of initiatives operating per country. Source: own data, N = 71 initiatives operating across multiple locations.

Table 1
Results of negative binomial models.

	Model 1	Model 2	Model 3	Model 4	Model 5
Dependent variable: number of initiatives per country					
(Intercept)	2.442 (0.167)***	2.417 (0.166)***	2.876 (0.202)***	2.826 (0.188)***	0.915 (0.548)+
Percent electricity access	−0.013 (0.002)***	−0.011 (0.003)***	−0.014 (0.003)***	−0.013 (0.003)***	−0.009 (0.003)**
Emissions		−0.058 (0.034)+	−0.050 (0.033)	−0.047 (0.034)	−0.122 (0.040)**
Governance			0.0429 (0.110)***	0.353 (0.110)**	−0.382 (0.120)+
Fatalities from climate change				−0.160 (0.069)*	−0.154 (0.126)
IPR protections					0.423 (0.088)***
Absorptive capacity					−0.011 (0.009)
Number of observations (countries)	128	126	126	115	59
AIC	637.26	626.01	614.8	563.5	291.12

Significance: $p < 0.0001$ ***$p < 0.001$ **$p < 0.01$* $p < 0.05$+Unstandardized regression coefficients, standard errors in parentheses.

constant. A one unit change in the dependent variable results in the log of expected counts changing by the regression coefficient. The final model (5) includes all variables and has the strongest predictive power.

We provide detailed information on variable distributions, model comparisons and robustness checks in the Appendix. The next section discusses the results of the negative binomial regressions.

4. Results and discussion

The empirical results paint a mixed picture: low-carbon technology transfer initiatives appear to address some, but not all, of the gaps left by FDI. Initiatives occur less often on average in countries with high rates of electricity access, and countries with good governance scores (once threats to competitive advantages were introduced into the model). However, there may be a trade-off at work, as higher rates of IPR protections are correlated with a higher number of initiatives in a country. The IPR variable is highly significant and seems to better predict the number of initiatives than governance. Absorptive capacity was not significant, although the direction suggests that countries with higher capacities may be recipients of fewer initiatives.

The variables measuring climate factors – emissions and climate vulnerability –correlate significantly with the number of initiatives per country. In models 2 and 5, countries with higher emissions had significantly fewer initiatives, suggesting that avoiding carbon lock-in may be an important goal. Model 4 shows a significant and negative relation with the number of fatalities from climate change, meaning that countries with more deaths may see fewer initiatives. However, in the final model, this is no longer significant (although the sign remains negative).

These findings offer several important insights. First, countries with low rates of electricity access have more initiatives on average, which suggests that one of the main goals indeed is to make up for private companies not investing due to the difficulties of setting up new infrastructure and lack of market pull. It further suggests that is a development angle to this type of technology transfer. If IP protections are taken into account, initiatives may also address another problem typically considered causal for lacking private sector activity: governance challenges. Initiatives seem to intervene more often in those countries where private finance would find it too risky to invest. Moreover, initiatives appear to respond to emission trajectories and target future emissions, which is an important aspect given that per capita emissions are due to increase in Africa and Asia.

Second, however, this does not necessarily mean that these efforts address all aspects of the technology gap. The regression results suggests that initiatives occur more frequently in those counties with stricter property rights protections. Rather than remedying the shortcoming of poor IPR regimes, they seem to follow the general pattern of private investment in this regard. Innovative capacity shows a negative relationship with the presence of initiatives, hinting at initiatives avoiding countries where a threat to competitive business advantages is perceived. While additional research is needed to explore this pattern, a reason could lie in the fact that most transfer initiatives are PPPs, which are meant to give companies ownership in the process. Initiatives may to some extent, therefore, align with the interests of technology-holders not to lose control of value creation as suggested by Bayer and Urpelainen (2012); and with the interests of developed countries to maintain the existing IPR regime in international technology transfer governance (Oh, 2019). While it is beyond the scope of this paper to explore the dynamics at play within initiatives themselves, especially public-private partnerships, this could be an important avenue for future research.

Preventing a repetition of uneven development patterns rests on effective technology transfer, a precondition for which is the ability to adapt technologies to local needs. Yet, although they were specifically selected for their focus on technology transfer, the mapping indicates that most initiatives did not simultaneously promote diffusion and transfer. A strong focus rests on transferring goods and some skills, but less on knowledge and innovative capacity-building. In other words, the predominant focus on hardware may result in technology diffusion –the deployment of renewable energy. This is laudable per se, and indeed a good cause for setting up transfer initiatives. It will, however, not be enough for veritable technology transfer and innovation. In other words: it will not result in 'green industrialization' as a development model, which is an explicit policy goal of some countries who hope to follow China's example (Behuria, 2020; Bazilian et al., 2020). The fact that knowledge and capacity-building are neglected across technology transfer mechanisms confirms previous research (De Coninck and Puig, 2015) and calls for policy action so as to bridge the gaps between countries with access to low-carbon technology and those without, and limit the risk of an uneven energy transition (Eicke and Goldthau, 2021).

Third, climate justice may not be addressed by the initiatives assessed in the sample. Clearly, initiatives occur more frequently in countries with low electricity access, which points to concerns with distributive justice. However, climate risk, which we had expected to increase the number of initiatives present, is either non-significant or negative. The model selection and validation showed no significant relationship between the Climate Risk Index and number of technology transfer initiatives; models including variables representing number of deaths from climate change suggest that initiatives may occur less often in high-risk countries. The lack of attention to climate risks suggests a mismatch between vulnerability to climate change and targeted technology transfer– perhaps reflecting increased awareness of climate risks to investment (Zamarioli et al., 2021). This is a concerning finding as the risks from climate change for vulnerable regions and populations will only become more severe over time.

5. Conclusion and policy implications

Technology transfer remains a concern for developing countries, and a condition for many governments to achieve their NDCs. Although the research on clean technology transfer has highlighted important successes, such as China's local content requirements and industry-building, we point out that this is likely the exception rather than the rule. This is because policies to promote this extent of tech transfer require not only high technical capacities, but also political and economic clout. In most contexts, know-how is what ensures technology-holders' competitive advantages and will therefore not be transferred. Furthermore, many developing countries lack investment from the private sector in low-carbon energy, which is key for technological spillovers, raising the issue of a technology gap. Given the commitments of the international community to climate justice and avoiding carbon lock-in, we argue that tech transfer initiatives may be an important tool for developing countries.

Our empirical findings suggest that initiatives may begin to address certain aspects of this gap, at least when it comes to countries with small electricity markets and lower emissions. However, initiatives appear to occur less often in countries with higher climate risks. In addition, countries where competitive advantages are threatened by low IPR protection and higher innovative capacities see fewer initiatives on average. Combined with the focus on technology diffusion over sustained knowledge-sharing and capacity-building, this suggests that even initiatives with the explicit purpose of facilitating technology transfer may not be able to address the challenge.

Although initiatives to some extent respond to development needs, they cannot be expected to remedy the 'North-South divide' by making up for markets. They are but one piece of the complex puzzle of low-carbon technology transfer, which also depends on the domestic and international political contexts, and the governance of innovation and energy systems change (Baker and Sovacool, 2017; Kuzemko et al., 2019; Kirchherr and Urban, 2018). Our empirical analysis measures only the extent to which a given country is targeted by technology transfer initiatives, but not the initiatives' success, or the differences between transferred technology types. In addition, the focus on global dynamics may miss out on regional differences, which are clearly relevant. As with any mapping exercise, there may be initiatives omitted from the sample, especially because researchers relied on their languages spoken and translation software for desktop research and communication. Finally, the analysis is, to some extent, exploratory in nature: it assesses where initiatives occur at one point in time, but does not grasp the dynamic evolution of initiatives. Given these limitations we cannot fully rule out the possibility of reverse causality or omitted variable biases.

The present investigation raises several points for further research. First, research on low-carbon transitions needs to differentiate between diffusion and transfer, and appreciate the difference between importing a technology and adapting it to local contexts, enhancing innovation capacity and delivering long-term added value. Renewable and low-carbon energy technology offers promising empirical avenues in this regard, as relevant 'hardware' and 'software' are concentrated among a few technology leaders. Second, we highlight the need to look beyond FDI to technology-sharing through alternate means, in order to understand how the lack of software transfer may be remedied. This could include diving deeper on specific configurations such as multi-stakeholder partnerships (Morsink et al., 2011) which remain an understudied element of the low-carbon energy transition. Further conceptual and empirical work is needed on the design of international tech transfer mechanisms under the UNFCCC and WTO, and on global climate and energy technology governance generally, especially the extent to which it reflects the interests and priorities of developing countries (Oh, 2019). Third, work on prospects and challenges of 'green pathways' as a strategy of industrialization for developing countries (Baker and Sovacool, 2017) may wish to further explore ways for technology importers to improve technology flows. Here, an interesting starting point may be in trade and regional cooperation, especially whether pooling resources and demand can help developing countries gain the political and economic clout needed to employ policies like local content requirements.

On the policy side, this paper points to significant blind spots pertaining to low-carbon technology transfer initiatives, and in the global climate and energy governance architecture. The key message to all policymakers is that they cannot count on 'the market' nor existing international mechanisms like the UNFCCC to deliver skills and knowledge-sharing alongside hardware. Although markets may deliver diffusion to larger countries, and tech transfer initiatives address one small part of the gap they leave, the size of the challenge remains immense and will require concerted effort at all levels. Actors who frame the energy transition as delivering 'green development' must take into account the risk of technological divergence extending into in the low-carbon domain. If policymakers promise 'leapfrogging' but do not deliver, they risk political backlash in the longer term. For tech transfer initiative funders, one pressing policy imperative lies in understanding and addressing these initiatives' apparent bias towards countries with relatively high IPR protections. It will be particularly important to revisit the institutional setup of such mechanisms, to see whether there exists alignment with the interests of involved parties. Likewise, funders should ensure that initiatives target those countries most vulnerable to climate change, as our analysis suggests that they may see less technology transfer.

Given the imperative to prevent dangerous climate change, and the necessity to meet developing countries' NDCs, further mechanisms are needed to encourage tech transfer. Here, we suggest that linking climate and trade could offer an opportunity to mainstream technology transfer, if technology-importing countries cooperate to negotiate favorable terms by, for example, pooling demand. Research on regional trade agreements suggests that innovation provisions combined with appropriate enforcement mechanisms can be one way to encourage transfer over time (Martínez-Zarzoso and Chelala, 2021). Although enforcing violations of these measures may be complicated, least developed countries in particular are promised tech transfer under TRIPS Article 66.2, and the WTO's dispute settlement mechanism would provide an avenue for enforcement that is missing from other clean tech transfer spheres like the UNFCCC. Complementing this, the rich world needs to deliver on funding for key actors and agencies working on tech transfer.

This is all the more pressing as economic blocs like the EU and US consider implementing border carbon adjustments, without accounting for the low-carbon technology gap and thereby the vulnerability of their trading partners (Eicke et al., 2021). They should take seriously the need for technological support with trade partners and provide technical and financial support to help their decarbonization. Short of this, the developing world may risk carbon lock-in in the long term.

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CRediT authorship contribution statement

Silvia Weko: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft. **Andreas Goldthau:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

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 gathered by researchers available in supplementary material; other data gathered from public sources listed, see Appendix for further information.

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Appendix A. Supplementary data

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