Global climate change mitigation technology diffusion: a network perspective

Zhang, J.; Ballas, D.; Liu, X.

Energy Economics 133 (2024) 107497

Contents lists available at ScienceDirect

Energy Economics

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

Global climate change mitigation technology diffusion: A network perspective

Jianhua Zhang [*], Dimitris Ballas, Xiaolong Liu

Department of Economic Geography, Faculty of Spatial Sciences, University of Groningen, the Netherlands

ARTICLE INFO

JEL:
O33
Q40
Q48
Q55

Keywords:
Climate change mitigation technologies
Diffusion networks
International knowledge spillovers
Energy transition
Intra-firm ownership

ABSTRACT

There is a rapidly growing number of studies on transnational climate change mitigation technology (CCMT) diffusion. Most of these studies have adopted a bilateral perspective, treating countries as primary agents driving the diffusion process. However, CCMT diffusion typically arises from the interactions between firms and involves strong network effects. In this paper, we explore the global CCMT diffusion from a network perspective, with multinational corporations (MNCs) as network makers. We first propose a methodology to construct the global CCMT diffusion networks, leveraging CCMT-related patent data, intra-firm relationships, and business scales of the selected MNCs. We then calculate the network capital for each country, utilizing it as the input for the econometric analysis to investigate the network effects on CCMT development. The network statistical analysis reveals an uneven geographical distribution of network capital, underscoring the presence of global disparities in CCMT development. Moreover, the econometric analysis identifies significant network effects originating from linkage volumes and structural positionalities within the CCMT diffusion networks.

1. Introduction

An expanding coalition of countries, cities, firms, and institutions is collaboratively striving to cut greenhouse gas emissions to as close as zero by 2050 (IEA, 2021). However, achieving net-zero emissions by mid-century presents challenges primarily due to the magnitude of the fluxes (Allen et al., 2022; Arora and Mishra, 2021). There is a substantial emission gap between the projected emissions based on the Nationally Determined Contributions announced prior to COP26 and the emission levels necessary to align with modeled mitigation pathways that limit global warming to 1.5 °C or below 2 °C (Chen et al., 2022; ICPP, 2023). In this regard, accelerating the development and diffusion of CCMTs presents a strategic way to bridge the gap between political rhetoric and net-zero carbon reality (Herman, 2022; Probst et al., 2021; Vakulchuk et al., 2020; Wang et al., 2021).

Several strands of literature have examined the drivers of CCMT development. On the one hand, some literature suggests that technology development is a path- and place-dependent process (Aguirre and Ibikunle, 2014; Martin, 2021; Monasterolo et al., 2019; Nelson and Winter, 1982). This perspective emphasizes the significance of domestic factors such as policies (Popp et al., 2011) and social-technical configurations (Hansen and Coenen, 2015; Przychodzen and Przychodzen, 2020) in shaping technology development. On the other hand, recent literature sheds light on the role of cross-border CCMT diffusion driven by international knowledge transfer (Fadly and Fontes, 2019; Holm et al., 2020; Lopolito et al., 2022; Shih and Chang, 2009; Yu et al., 2022). However, most recent empirical studies have two potential limitations. First, they tend to focus on bilateral relationships between countries as a measure of international connections. Yet, technology diffusion is not a straightforward bilateral process; it often involves strong network effects originating from agents' indirect linkages (Aldieri et al., 2019; Derudder, 2021; Halleck-Vega et al., 2018; Jackson et al., 2017). The second concern arises with the idea of countries as agents in transnational CCMT diffusion. While countries certainly wield significant influence in certain industries like aerospace and nuclear energy (Vega and Mandel, 2018), in the case of most CCMTs, the diffusion process is ultimately shaped by interactions at the firm level (Chaney, 2014; Horbach and Rammer, 2018; Yeung, 2005).

To address these issues, this paper adopts a network perspective to explore the network effects arising from the global CCMT diffusion processes on CCMT development. In network theory, a network consists of nodes and links that display a pattern of connections (Freeman, 2004). In this paper, we explicitly incorporate a critical sub-nodal level, namely firms, into the network structure, aligning with the approach

* Corresponding author at: Faculty of Spatial Sciences, P.O. Box 800, 9700AV, Groningen, the Netherlands.
E-mail address: jianhua.zhang@rug.nl (J. Zhang).

https://doi.org/10.1016/j.eneco.2024.107497
Received 15 December 2022; Received in revised form 6 March 2024; Accepted 17 March 2024
Available online 24 March 2024

employed in relevant previous studies (see, e.g., Taylor, 2001, Sassen, 2013 and Neal et al., 2021). We argue that it is the firms operating within and across countries that essentially shape countries as nodes within the global diffusion networks (Beaverstock et al., 2000; Sassen, 2013; Taylor and Derudder, 2015; Taylor, 2001; Wall et al., 2011).

In this regard, the selection of firms and the types of their relationships are crucial. We focus on the intra-firm relationships of multinational corporations (MNCs) with significant CCMT innovation capacities for several reasons. First, MNCs possess extensive knowledge pertaining to innovative technologies, owing to their substantial R&D investment and their pursuit of economic gains (Hotz-Hart, 2000; Popp, 2020). Second, certain types of knowledge are more prone to internal transmission (Gaur et al., 2019; Markusen, 1995; Spraggon and Bodolica, 2012). For example, tacit knowledge tends to circulate more efficiently among individuals or groups within a well-structured framework, facilitated by established organizational routines, ultimately becoming an integral component of a firm's cumulative knowledge bases (Grant and Phene, 2022; Howells, 1996). Furthermore, to prevent knowledge from falling into a competitor's hands and to maximize the returns on R&D investment, strategic innovations are often held in strict confidence (Abdul Wahab et al., 2009; Archibugi and Filippetti, 2018; Liebeskind, 2009). Third, the internationalization strategies and local market operations of MNCs facilitate knowledge transfer on a global scale (Bathelt et al., 2004; Hitt et al., 2016). Finally, cross-border intra-firm relationships encompass dynamic interactions between headquarters and subsidiaries, inherently promoting international knowledge diffusion through these connections (Athreye et al., 2016; Ferraris et al., 2020; Van Wijk et al., 2008).

Specifically, we first identify the 228 most innovative MNCs in CCMTs based on their patent activities up to and including 2021. We then construct the CCMT diffusion networks, incorporating data on sustainable innovation capacities, business scales, and geographical information regarding the headquarters and subsidiaries of these 228 MNCs. The weighted networks involve 656,586 transnational linkages across 185 countries/regions. Once these networks are established, we calculate the network capital of each country within the diffusion networks with respect to linkage volumes and structural positionalities. Finally, we incorporate these network capital measures into the econometric regression models to investigate the network effects originating from the diffusion networks on CCMT development.

This paper offers two innovations. First, we investigate the global CCMT diffusion networks with a focus on the global deployment of sustainable innovation MNCs, whereas the existing empirical studies primarily consider countries as network makers. Moreover, over the past decades, numerous studies have constructed global relational networks using data from various types of firms, including MNCs (Alderson and Beckfield, 2004), advanced producer service firms (Beaverstock et al., 2000; Taylor and Derudder, 2015), and financial firms (Diebold and Yılmaz, 2014). However, we are not aware of any studies that approach global corporate networks in the context of sustainability transitions and CCMT diffusion. Second, we adopt a network perspective to assess the impact of different forms of network capital on CCMT development. Existing literature mainly focuses on bilateral relationships. In contrast, our network-based approach not only captures the effects of direct linkages but also systematically provides insights into network effects arising from structural positionalities within the networks.

This paper proceeds as follows. In Section 2, we briefly review the relevant literature, highlighting the necessity of integrating network capital into analysis of factors that influence CCMT development. In Section 3, we outline the methodology for network statistical analysis and econometric model specification. Section 4 presents the data, while Section 5 discusses the findings. We conclude and propose directions for future studies in Section 6.

2. Literature review

Literature on technology development and diffusion is pervasive. Technological progress is often considered as a path- and place-dependence process (Boschma et al., 2018; Heimeriks and Boschma, 2014; Nelson and Winter, 1982). In the context of CCMTs, existing research mainly identifies relevant domestic determinants that influence green innovations from a host country perspective (Halleck-Vega et al., 2018; Lopolito et al., 2022). These factors include technological relatedness (Hidalgo et al., 2018), reliance on natural resources (Best, 2017), and socio-economic configurations including environmental and energy policies (Johnstone et al., 2010), market liberalization (Nicolli and Vona, 2019), and access to financial capital (Nicolli and Vona, 2016; Veugelers, 2012). There exist more comprehensive studies that examine the role of these domestic determinants in CCMT development (see, e.g., Aguirre and Ibikunle, 2014, Popp et al., 2011 and Przychodzen and Przychodzen, 2020).

With increasing globalization, recent literature has begun to explore the impact of international relationships on transnational technology diffusion, subsequently driving technological advancements (see, e.g., Ferrier et al., 2016, Lopolito et al., 2022, Perkins and Neumayer, 2005 and Popp, 2020). Countries' technological development reaps several benefits from transnational technology diffusion (Mancusi, 2008). From the perspective of individual nation/state, access to the knowledge embedded in the technologies disseminated from abroad is instrumental in advancing their own technological capacities (Hansen and Lema, 2019). This access is crucial for mitigating uncertainties and risks associated with inventing and introducing new technologies (Giuliani et al., 2016). New technologies are generally costly and unreliable during the incubation and early commercialization stages (Negro et al., 2012). In particular, CCMTs often carry significant uncertainties concerning their investment returns (Shakeel et al., 2017). Furthermore, countries can enhance the efficiency of their energy R&D investments by leveraging knowledge generated elsewhere (Bosetti et al., 2008). This is particularly relevant for the developing countries who can benefit from the technological advancements of the forerunners (Pegels and Altenburg, 2020).

When considering global challenges, transnational CCMT diffusion assumes a crucial role in achieving global sustainability transition goals. Given that most developing countries orient their policies on poverty reduction and economic modernization, the landscape of CCMT innovations is currently dominated by a handful of highly developed countries (IEA, 2021; Kaygusuz, 2012; Probst et al., 2021). Since innovations already exist in certain countries, facilitating the transfer of these technologies from inventors to late adopters becomes paramount in addressing global challenges (Ockwell et al., 2008).

Current literature outlines three primary channels through which technologies can be transferred across borders. The first channel is international trade, which allows countries to acquire products and the associated knowledge that have been innovated or produced elsewhere (Garsous and Worack, 2022; Keller, 2004). This knowledge encompasses various aspects, including production costs, technical performance, industrial chains, and experience, all of which is enriched through both formal and informal interactions among trading partners (Athreye et al., 2023). It is also suggested that the intensification of market competition has increased the demand for new technologies. The second channel involves foreign investment facilitated by MNCs. MNCs produce, manufacture and control most advanced technologies worldwide (Dunning and Lundan, 2008; Younas, 2021). When MNCs expand into foreign markets, they export their experience and innovations to other countries through project investments or subsidiary operations, thereby enhancing the technological capacities of the recipient countries (De Beule and Van Beveren, 2019). The presence of MNCs is widely acknowledged for its role in facilitating the transfer of information, know-how, and skills associated with cutting-edge technologies (Antras et al., 2009). The third channel involves licensing agreements with local firms. MNCs transfer knowledge abroad by selling their intellectual property rights to overseas companies (Casson and Wadeson, 2018). Licensing often avoids many potential trade barriers when compared to direct investments (Nagaoka, 2009).

In the context of CCMT diffusion, recent literature has explored how these channels operationalize with different types of relationships between countries (De Coninck and Sagar, 2015; Fadly and Fontes, 2019; Mandel et al., 2020). However, there are two potential drawbacks. First, literature mainly focuses on bilateral relationships, treating each pair of countries independently. The second concern arises from the notion that countries are the primary agents in the process of CCMT diffusion.

The first drawback lies in neglecting the network effects, which facilitate the diffusion of technologies between indirectly connected countries through intermediaries. For example, even in cases where there is no direct connection between countries A and C, technologies and knowledge could still be exchanged between them via an intermediary country like B. This means that once knowledge is acquired by the immediate partners of innovators, it can be further disseminated to the partners of the direct partners and so forth (Faems et al., 2020; Ferrier et al., 2016). Recent network-based models of technology diffusion have approached how knowledge spreads across various network configurations, suggesting the significance of network capital in international knowledge acquisition (Allan et al., 2014; Chesbrough, 2003; Harris, 2011).

Network capital, a relational asset derived from complex interactions with external actors, plays a vital role in facilitating knowledge exchange by establishing network connections to distant resources (Huggins et al., 2012; Huggins and Thompson, 2014). Actors with higher network capital tend to occupy advantageous positions to reinforce local innovation efforts owing to their enhanced capacity to transfer complex knowledge across spatial boundaries (Rodríguez-Pose and Crescenzi, 2008). Nevertheless, previous research on CCMT diffusion has predominantly embraced a bilateral perspective, with limited exploration of network effects. A notable exception is the work of Halleck-Vega et al. (2018). In their study, the authors adopt a network-based approach to analyze the global transnational diffusion of wind energy technologies from 1983 to 2016. They access various network centralities, including degree, closeness, betweenness and eigenvector, across 94 countries. Their findings highlight the significant network effects arising from the structural positionalities within these networks, which play a pivotal role in facilitating the transnational diffusion of wind energy technologies.

Nevertheless, within these studies, the idea of countries acting as agents of CCMT development and network makers of global CCMT diffusion networks raises another concern. Most network analysis relies on a two-level structure, consisting of members as nodes, i.e. countries, and their interactions that constitute the networks. While the literature notes that cities or countries function as nodes in the networks, they are not the primary agents in the formation of networks (Beaverstock et al., 2000; Taylor and Derudder, 2015; Taylor, 2001, 2019). Instead, the interlocking network model introduces the concept of sub-nodes as the foundational element of network formation (Derudder, 2012; Taylor and Derudder, 2015; Taylor, 2001, 2011). It is suggested that the behavior of the sub-nodes, i.e. firms, play the fundamental roles in shaping cities or countries as nodes within the network (Derudder and Parnreiter, 2014; Liu and Derudder, 2012; Neal et al., 2021).

Our paper demonstrates how cross-border activities of MNCs establish connections between countries. We identify these relationships between countries by essentially analyzing the behaviors of firms. This is particularly important in the context of CCMTs, as transnational diffusion primarily emerges from interactions between private firms (Horbach and Rammer, 2018). While countries undeniably play important roles in CCMT diffusion, they often function as intermediaries or facilitators, for instance, by offering incentives and providing R&D investments to support firms (Moss, 2009). Accordingly, this paper aims to tackle these two potential challenges and pitfalls by examining the roles of sustainable innovation MNCs in accelerating CCMT diffusion. We account for the network capital generated throughout the CCMT diffusion process when assessing the factors that influence CCMT development.

3. Methods

The methodological framework employed in this paper consists of two parts. Section 3.1 introduces the method for network statistical analysis. Drawing from Derudder (2021) and Taylor and Derudder (2015), we analyze firms' behaviors with the goal of constructing country-level networks. Section 3.2 discusses the econometric specification, where we incorporate the network variables calculated in Section 3.1 into the econometric regression model to examine the relationship between network capital and CCMT development.

3.1. Network statistical analysis

In this analysis, the global CCMT diffusion networks are represented by weighted intra-firm networks of MNCs with substantial sustainable innovation capacities. This is mainly motivated by their extensive knowledge bases, global deployments, and internal knowledge flows within them resulting from intra-firm relationships. To construct these networks, we identify the top MNCs with strong sustainable innovation capacities in CCMTs based on their CCMT-related patent activities. We select MNCs that have obtained a minimum of 15 CCMT-related patents up to and including 2021. We set a threshold of 15 CCMTs to ensure that the selected MNCs devote substantial resources to CCMT research during the study period, excluding those only involved in short-term, sporadic activities. This threshold also filters out smaller MNCs with less influence in the global CCMT landscape. This results in a total of 228 MNCs worldwide.[1] Subsequently, we construct firm-to-country two-mode networks based on the country-level geographical locations of these MNCs' headquarters and subsidiaries. These networks are assigned weights using information on their sustainable innovation capacities and business scales. Finally, we convert these two-mode networks into country-dyad one-mode networks, which allow us to calculate the network capital for each country.

3.1.1. Constructing weighted matrices

When constructing the weighted matrices, we consider three factors that potentially influence the magnitude of knowledge transfer, including the number of MNCs within a country, the sustainable innovation capacities of these MNCs, and their business scales.

Regarding the first factor, we quantify it by counting the presence of selected MNCs' headquarters and subsidiaries in each country. Similar to Alderson and Beckfield (2004), Wall et al. (2011) and Derudder and Parnreiter (2014), we measure the intensity of CCMT diffusion between two countries by considering the cumulative number of intra-firm linkages that connect the home countries, where headquarters are based, to the host countries, where subsidiaries are located. Mathematically, the directed network $G(V, E)$ consists of a set of countries $N = |V|$ and a set of linkages $E = |\varepsilon|$, fully presented by its adjacency matrix $M = \{m_{ij}\}$. In this binary matrix, each element $m_{ij} = \{0, 1\}$ indicates whether the subsidiary of the MNC headquartered in country i is present (1) or absent (0) in country j in 2021. Here, we assign the adjacency matrix M a weighted matrix $W_1 = \{w_{ij}\}$, where $w_{ij} = \sum_{a=1}^{n} v_{i,a} * v_{j,a}$. It quantifies the overall strength of the connection between any given pair of countries i and j by summing the number of subsidiaries located in country j across all MNCs $(a \rightarrow n)$ which have their headquarters in country i. Each element of the adjacency matrix M_1 is

[1] For MNCs with CCMT rankings below 228, there is a significant decrease in the total number of CCMT-related patents.

denoted as

$$\{m_{ij}{*}w_{ij}\} = \left\{m_{ij}{*}\sum\nolimits_{a=1}^{n} v_{i,a}{*}v_{j,a}\right\} \tag{1}$$

Next, building on M_1, we consider variations in sustainable innovation capacities among the MNCs. We assign a normalized patent weight $W_p = \{p_n/P\}$ to each element of the adjacency matrix M_1, where p_n represents the number of patents held by MNC n, and P represents the total patents held by these 228 MNCs. Consequently, each element in the adjacency matrix M_2 can be expressed as

$$\left\{m_{ij}{*}w_{ij}{*}\frac{p_n}{P}\right\} = \left\{m_{ij}{*}\sum\nolimits_{a=1}^{n} v_{i,a}{*}v_{j,a}{*}\frac{p_a}{P}\right\} \tag{2}$$

Finally, we consider the business scales of these 228 MNCs, which suggest their diverse knowledge bases and influence potential. To assign greater weights to MNCs with larger business scales, we introduce a normalized turnover weight $W_t = \{t_n/T_n\}$ to each element of the adjacency matrix M_2. Here, t_n represents the average turnover of firm n from 2000 to 2021, and T is the sum of average turnovers for these 228 MNCs over this period.[2] Each element of the adjacency matrix M_3 is denoted as

$$\left\{m_{ij}{*}w_{ij}{*}\frac{p_n}{P}{*}\frac{t_n}{T}\right\} = \left\{m_{ij}{*}\sum\nolimits_{a=1}^{n} v_{i,a}{*}v_{j,a}{*}\frac{p_a}{P}{*}\frac{t_a}{T}\right\} \tag{3}$$

The subsequent analysis is based on the adjacency matrix M_3, which incorporates all three factors that can influence a firm's technology and knowledge transfer capacities.

3.1.2. Calculating network capital

Upon constructing the company-to-county two-mode weighted networks, we convert them into country-dyad one-mode networks. In this study, we consider the network as an outcome rather than a process, aiming to assess the network capital of countries across various dimensions of centrality measures. Consequently, we employ centrality-based network analysis techniques, rather than techniques that are mainly used for network formation studies such as the tie-oriented exponential random graph model (Lusher et al., 2013). Following the approach adopted in relevant studies (see, e.g., Huggins et al., 2012, Huggins and Thompson, 2014 and Shi et al., 2022), network capital is measured with respect to linkage volumes and structural positionalities, considering whether the capital is generated through direct linkages or structure positions.

Linkage volumes reflect a country's capacity to establish interactions with other countries. We measure linkage volumes by considering transnational intra-firm linkages, encompassing weighted indegree, weighted outdegree, and weighted total degree. Specifically, weighted indegree represents the sum of weighted inbound connections, denoting the number of subsidiaries received by a country. It provides insight into a country's centripetal force and attractiveness to source countries. Weighted outdegree measures the sum of weighted outbound connections, indicating the number of headquarters located in a country. It reflects a country's centrifugal force and prestige in expanding its influence within the network. Weighted total degree is the sum of weighted indegree and weighted outdegree, calculating the total weighted connections occurring within a country's borders. This metric represents a country's self-maintained capacity within the network (Table 3). Mathematically, following Newman (2018) and Alderson and Beckfield (2004), the degree centrality of country v is given by

[2] We use turnover data starting from 2000 mainly due to the unavailability of turnover data for many firms before 2000. Furthermore, among these 228 MNCs, 6 of them were established after 2000. We calculate their average turnover by dividing the total turnover between the year of their establishment and 2021 by the number of years since their establishment.

$$D(v) = \frac{Td_v}{|N|-1} \tag{4}$$

where N represents the set of nodes in the network, and Td_v denotes the total degree of country v, i.e., the count of linkages that are directly connected to country v. Td_v consists of two components, namely indegree Id_v measures the number of incoming linkages to country v, and outdegree Od_v represents the number of outgoing linkages from country v.

Furthermore, structural positionalities evaluate a country's significance within the network by considering its connections with influential counterparts. These are assessed using metrics including eigenvector, betweenness, and closeness. Specifically, eigenvector evaluates a country's ability in enhancing its standing by establishing its connections with influential peers. It suggests that a country may not be advanced in CCMTs, it can still benefit from being highly connected to countries with high CCMT capacities. Mathematically, the eigenvector $E(v)$ of country v is written as

$$E(v) = \frac{1}{\lambda}\sum\nolimits_{t\in M(v)} x_t = \frac{1}{\lambda}\sum\nolimits_{t\in G} a_{vt}x_t \tag{5}$$

where $M(v)$ is a set of neighbours of v, a_{vt} is 1 when v and t are directly connected, and λ is a constant. Betweenness quantifies how frequently a country appears on the shortest paths between two indirectly connected countries, indicating its gateway position within the network. The betweenness $B(v)$ of country v is written as

$$B(v) = \sum\nolimits_{u\neq v\neq t\in V} \frac{\sigma_{u,t}(v)}{\sigma_{u,t}} \tag{6}$$

where σ_{ut} is the number of shortest paths between u and t, and $\sigma_{u,t}(v)$ is the number of shortest paths between u and t that pass through country v. Lastly, closeness quantifies a country's network proximity to others by averaging the shortest path lengths from that country to every other country within the network. The closeness measure $C(v)$ of country v is written as

$$C(v) = \frac{1}{\sum\nolimits_{u\in N/v} d(v,u)} \tag{7}$$

where N is the set of countries in the network, and $d(v,u)$ is the length of the shortest paths from v to all the other vertices u. We employ Gephi software for network visualization and network capital calculation.

3.2. Econometric regression analysis

To explore the relationship between network capital generated during the CCMT diffusion process and CCMT development, we estimate the following econometric equation:

$$Y_i = \alpha + \beta_1 N_i + \beta_2 X_i + \varepsilon \tag{8}$$

where Y_i is the level of CCMT development in country i in 2021, proxied by the logarithm of per capita net renewable electricity production. The inherent unpredictability of renewable energy resources introduces several challenges during the renewable electricity production process (Denholm et al., 2021). First, it requires balancing supply and demand, which involves addressing short-term fluctuations of variable renewable energy resources, diurnal mismatches, and seasonal mismatches. This is particularly evident in technologies reliant on short-term weather conditions, such as highly distributed solar photovoltaics and wind (Rai and Henry, 2016; Zhang et al., 2023). Second, it requires the design of reliable inverter-based grids to ensure frequency stability, voltage stability, rotor angle stability, power protection, and voltage control (Kundur et al., 2004). Furthermore, economic viability entails considerations of advancing materials, manufacturing processes, energy conversion systems, as well as establishing a resilient and stable supply chain. Tackling these challenges requires integrating various technologies, and CCMTs offer numerous solutions. For example, Y02B highlights technologies related to end-user applications, Y02E emphasizes energy generation through various renewable energy sources, Y02P concentrates on technologies in the production or processing of goods and products, Y02T encompasses solutions for electric vehicles, and Y04S focuses on power networks operations and smart grids. Therefore, we utilize per capita renewable electricity production as a proxy to gauge a country's development level in CCMTs. The rationale is that addressing the challenges mentioned often requires the effective and innovative integration of various CCMTs. Similar to Fadly and Fontes (2019) and Przychodzen and Przychodzen (2020), this indicator is calculated by dividing the total renewable electricity net generation (in million kWh) by the total population of the country in 2021.

Furthermore, α is the intercept, β is the vector of coefficients of the independent variables, and ε represents the random error term. N_i is the network capital calculated in section 3.1, measured in terms of linkage volumes and structural positionalities. Linkage volumes consist of weighted indegree, weighted outdegree, and weighted total degree. Structural positionalities encompass eigenvector, betweenness, and closeness. Moreover, X_i represents the control variables obtained from the literature that could potentially influence renewable electricity generation. They include GDP per capita, energy policy instrument, and government's administrative capacity. GDP per capita accounts for the economic size and the development level of a country. Energy policy instrument, included as a dummy variable, aims to control for countries' different industrial strategies and policy support. We access whether a country had climate change mitigation policy in effect in 2021. These policies encompass measures related to energy efficiency, renewable energy, technology R&D and innovation, electrification, and carbon capture utilization and storage. The variable takes a value of 1 if a policy was in effect in a country in 2021 and 0 if no such policy was introduced or had ended by 2021. Lastly, government's administrative capacity is measured through regulatory quality and governance effectiveness. This variable reflects a government's ability to manage the local clean energy market and the ease or difficulty for private investors to conduct business in that country. See Section 4.2 for more information on the data sources used for these variables.

4. Data

4.1. Firm-level data

Three types of firm-level data are employed to construct the global CCMT diffusion networks, namely cumulative CCMT-related patent data up to and including 2021, country-level geographic data of headquarters and subsidiaries in 2021, and the average turnover of these 228 MNCs from 2000 to 2021.

We employ patent data related to CCMTs to identify the MNCs with high sustainable innovation capacities in CCMTs. Patent data is widely used to study knowledge generation and dissemination (Jaffe et al., 2002; Verendel, 2023), as well as to characterize the knowledge bases of countries and firms (Antonelli et al., 2010; Furman et al., 2002). The CCMT-related patent data comes from the Worldwide Patent Statistical Database (PATSTAT 2022 spring version), published by the European Patent Office, which contains data from 84 patent offices worldwide and covers all inventor countries (EPO, 2021; Popp et al., 2011). In 2012, the European Patent Office introduced the Y02/Y04S classification scheme within the PATSTAT to categorize technologies that are broadly associated with climate change mitigation (Angelucci et al., 2018; Li et al., 2020; Veefkind et al., 2012).Within the Y02/Y04S category, there are nine subcategories, as detailed in Table 1. Our study aims to provide an overview of the overall development and diffusion of CCMTs without placing specific emphasis on individual CCMTs. Therefore, our analysis encompasses all CCMTs categorized within the Y02/Y04S classification.

Fig. 1 illustrates the change in the number of CCMT-related patents for the top 10,000 firms or individuals from 2003 to 2021. Patents for all nine CCMTs have experienced substantial growths, particularly since 2009. Among these categories, the CCMTs related to energy generation, transmission and distribution (Y02E) exhibit the highest patent count, totaling 165,578 patents. Conversely, CCMTs associated with the capture, storage, sequestration or disposal of greenhouse gases (Y02C) display the lowest patent activity, with a total of 16,298 patents.

Table 1
Description of the Y02/Y04S category.

Y02	Climate change mitigation technologies
Y02A	Related to adaptation to climate change.
Y02B	Related to buildings, including housing and appliances or related end-user applications.
Y02C	Capture, storage, sequestration or disposal of greenhouse gases.
Y02D	Information and communication technologies aiming at the reduction own energy use.
Y02E	Related to energy generation, transmission and distribution.
Y02P	Related to the production or processing of goods.
Y02T	Related to transportation.
Y02W	Related to wastewater treatment or waste management.
Y04S	Smart grid technologies.

Source: EPO (2023).

The PATSTAT database contains various types of firms, including private versus state-owned firms, and multinational versus non-multinationals firms. We focus on MNCs as we are interested in firms that are capable of transnationally transferring technologies through intra-firm linkages. We choose the MNCs that have filed a minimum of 15 CCMT-related patents up to and including 2021. This results in 228 MNCs globally and a total of 145,716 patent in our sample.[3] Among these 228 MNCs, the average number of CCMT-related patents is 639.11, with Siemens AG having the most (6913) and Moderna Inc. the least (15).

Table 2 provides information on the leading MNCs which exhibit the most robust sustainable innovation capacities among firms in our sample. Fig. 2 compares the total count of CCMT-related patents for these 228 MNCs, categorized by their respective countries/regions of headquarters. Countries with more CCMT-related patents are shaded darker. These 228 MNCs are headquartered in 20 countries/regions. The top 10 countries boasting the largest number of CCMT-related patents are Japan (46,529), the US (31,972), Germany (22,967), South Korea (12,639), France (6077), the Netherlands (4631), the UK (4474), Mainland China (3255), Sweden (2485), and Switzerland (2224). Additionally, the figure provides a list of prominent MNCs headquartered in these 20 countries/regions with the highest number of CCMT-related patents.

We obtain ownership information, country-level locations of headquarters and subsidiaries in 2021, and turnover data from 2000 to 2021 for these 228 MNCs from Bureau van Dijk's Osiris database. In the cases of missing data for some firms in the Bureau van Dijk's Osiris database, we source them from the annual reports of the respective companies. In total, we extract a dataset comprising 88,863 ownership relationships, of which 22,277 are domestic and 66,586 are transnational. To construct global CCMT diffusion networks, we aggregate the data at the country level. These networks connect 20 home countries/regions with at least one outgoing corporate connection to 185 host countries/regions with at least one incoming corporate connection. For example, Siemens AG, headquartered in Germany, operates 1167 overseas subsidiaries across 85 countries in 2021. Among these, the US has the most Siemens AG subsidiaries, totaling 456, whereas countries like Oman and Tanzania have only one Siemens AG subsidiary each. We use the number of subsidiaries as a measure to assess the extent of Germany's connections with

[3] In the original database, 11 out of the top 240 firms are either state-owned or non-multinational. They have been excluded from our firm sample.

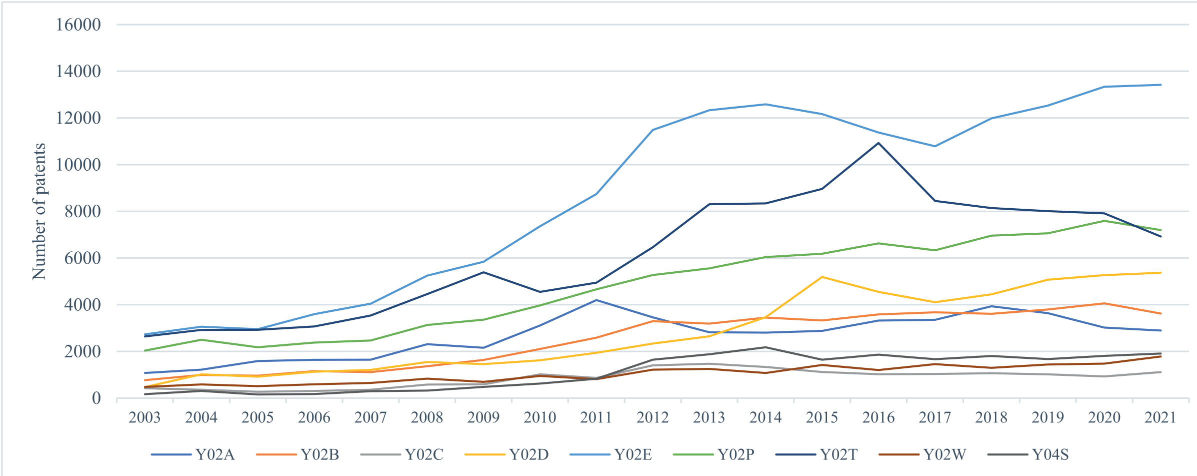


Fig. 1. Number of CCMT-related patents by type from 2003 to 2021.

Table 2
Top five sustainable innovation MNCs and relevant information.

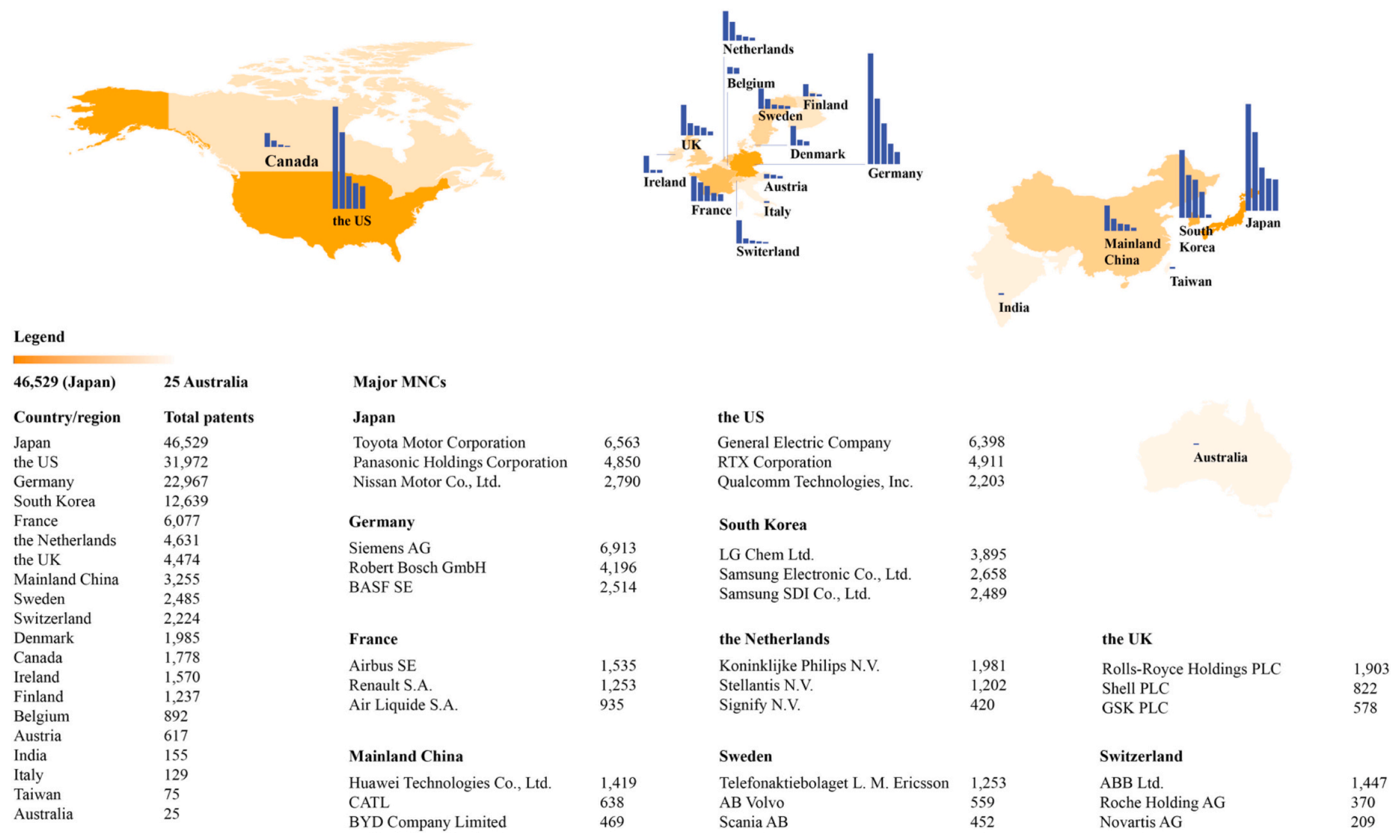
MNC	Number of CCMT-related patents	Average turnover 2000–2021 (billion USD)	Headquarter locations	Top 5 overseas subsidiary locations	Number of receiving subsidiaries
Siemens AG	6913	$ 91.415	Germany	USA	456
				China	81
				Canada	75
				UK	39
				India	34
Toyota Motor Corporation	6563	$ 207.749	Japan	USA	216
				China	29
				Canada	21
				Thailand	18
				Indonesia	14
General Electric Company	6398	$ 125.715	USA	UK	116
				Canada	76
				France	52
				Netherlands	45
				China	39
Raytheon Technologies Corporation	4911	$ 48.337	USA	Canada	63
				UK	50
				Australia	50
				France	20
				Italy	16
Panasonic Holdings Corporation	4850	$ 74.313	Japan	USA	274
				China	74
				Malaysia	24
				Canada	21
				Germany	20
				Spain	20

other countries facilitated through Siemens AG. The list of these countries/regions can be found in the Appendix.[4]

4.2. *Country-level data*

We source data for renewable electricity generation in 2021, the most current year for which the data is made available, from the U.S. Energy Information Administration.[5] Regarding the control variables, GDP per capita data is from the World Bank's Open Data platform.[6] Energy policy instrument information, reflecting countries' different industrial strategies and policy supports, are gathered from the Policies Databases of the International Energy Agency and the International Renewable Energy Agency.[7] This database is widely used in comparative studies of cross-country policies in clean technologies (Baldwin et al., 2017; Carley et al., 2017; Kim, 2020). Data on government's administrative capacity is collected from World Bank Worldwide Governance Indicators.[8] Table 3 presents details on variable operationalization, data

[4] We source information about countries and regions from the United Nations' list of member states.
[5] https://www.eia.gov/
[6] https://www.worldbank.org/en/home
[7] https://www.iea.org/policies
[8] https://info.worldbank.org/governance/wgi/



Country/region	Total patents
Japan	46,529
the US	31,972
Germany	22,967
South Korea	12,639
France	6,077
the Netherlands	4,631
the UK	4,474
Mainland China	3,255
Sweden	2,485
Switzerland	2,224
Denmark	1,985
Canada	1,778
Ireland	1,570
Finland	1,237
Belgium	892
Austria	617
India	155
Italy	129
Taiwan	75
Australia	25

Major MNCs

Country/region	MNC	Patents
Japan	Toyota Motor Corporation	6,563
	Panasonic Holdings Corporation	4,850
	Nissan Motor Co., Ltd.	2,790
the US	General Electric Company	6,398
	RTX Corporation	4,911
	Qualcomm Technologies, Inc.	2,203
Germany	Siemens AG	6,913
	Robert Bosch GmbH	4,196
	BASF SE	2,514
South Korea	LG Chem Ltd.	3,895
	Samsung Electronic Co., Ltd.	2,658
	Samsung SDI Co., Ltd.	2,489
France	Airbus SE	1,535
	Renault S.A.	1,253
	Air Liquide S.A.	935
the Netherlands	Koninklijke Philips N.V.	1,981
	Stellantis N.V.	1,202
	Signify N.V.	420
the UK	Rolls-Royce Holdings PLC	1,903
	Shell PLC	822
	GSK PLC	578
Mainland China	Huawei Technologies Co., Ltd.	1,419
	CATL	638
	BYD Company Limited	469
Sweden	Telefonaktiebolaget L. M. Ericsson	1,253
	AB Volvo	559
	Scania AB	452
Switzerland	ABB Ltd.	1,447
	Roche Holding AG	370
	Novartis AG	209

Fig. 2. Comparison of CCMT-related patents by country/region.

sources, and descriptions. Notably, the econometric analysis retains 173 countries/regions due to missing data on one or more crucial variables in some countries/regions, whereas the network statistical analysis maintains a sample size of 185.[9]

5. Results and discussion

5.1. Network statistical analysis results

Figs. 3–8 illustrate the global CCMT diffusion networks using six network capital measures. In these visualizations, each node represents a country, while the links between nodes reflect CCMT diffusion level among pairs of countries. Node size and the corresponding country name indicate the magnitude of network capital within each country, while edge thickness denotes the strength of CCMT diffusion between connected countries.

Specifically, Fig. 3 exhibits the global CCMT diffusion network based on weighted total degree, revealing an uneven spatial pattern. Countries with substantial network capital are predominantly clustered in Western Europe, North America, and East Asia, with Germany, the US, and Japan as regional centers. Regarding interregional linkages, the US maintains close ties with several Western European countries, especially the UK, the Netherlands, France and Germany. Among the connections between North America and East Asia, the link between the US and Japan stands out prominently. Furthermore, connections between Western Europe and East Asia are relatively weaker, except for the strong links with Japan and China. Additionally, intraregional interactions are less pronounced compared to interregional connections. There exists a significant proportion of interregional connections, irrespective of geographical distance. However, there are instances of diffusion that can be partly attributed to spatial proximity, such as Germany – the UK, the US – Canada, and Japan – China.

Table 4 compares the top 10 countries across six different network capital measures. Weighted outdegree analysis highlights that a small group of countries predominantly controls the majority of outbound connections. These influential countries include Germany, Japan, the US, the UK, South Korea, the Netherlands, France, Canada, Switzerland and Sweden. Together, these ten countries account for nearly 98.92% of all weighted outgoing connections. A similar, though less pronounced, pattern emerges when examining weighted indegree. The top 10 countries, namely the US, Canada, China, the UK, the Netherlands, France, Australia, Germany, Mexico, and India, account for approximately 63.91% of all incoming connections. Concerning structural positionalities, i.e. eigenvector, closeness, and betweenness, the US, China, Canada, the UK, and the Netherlands also emerge as significant hubs and authorities, reinforcing their dominant roles within the network. Finally, concerning bilateral linkages, the global CCMT diffusion network demonstrates a similar imbalance, with only 1.1% of country pairs accounting for approximately 50% of all connections.

Interestingly, some countries, such as Australia, excel in terms of linkage volumes but do not necessarily score highly in structural positionalities. Likewise, other countries, such as Belgium and Denmark, appear to hold significance in structural positionalities even though they may not stand out in terms of linkage volumes. This aligns with the findings of Vega and Mandel (2018), who argue that a country that is neither the most important source nor the most important technology

[9] These 12 countries/regions that are excluded in the econometric analysis are Andorra, Bermuda, Curacao, East Timor, Federated States of Micronesia, Gambia, Gibraltar, Ivory Coast, Liechtenstein, Monaco, San Marino, and Tonga with only a few connections in total.

Table 3
Description and summary statistics of the variable used.

Variable	Indicator	Obs.	Mean	Std. Dev.	Max	Min
Firm-level data						
Firms' sustainable innovative capacity	Numbers of CCMT-related patents granted in or before 2021	228	639.105	1,019.168	6,913	15
Firms' business scale	Firm's average annual turnover between 2000 and 2021 (billion USD)		32.011	46.575	309.673	0.080
Firms' ownership	Number of headquarters a country/ region host	20	11.4	19.313	77	1
	Number of subsidiaries a country/ region receives	185	357.443	1,673.149	21,637	1
Country-level data						
CCMT development	Net renewable electricity production in 2021 (million kWh)	173	44,825.44	200,218.6	2,363,284	1.22
	Net renewable electricity production per capita in 2021 (million kWh)		0.0016	0.005	0.052	6.20e-07
Network capital						
Weighted total degree	"Self-maintained capacity", scores measuring HQ-subsidiary linkages occurring within a country's boundary (see e.q. 4)		0.050	0.224	2.155	1.00e-06
Weighted indegree	"Attractiveness", scores measuring subsidiaries a country receives (see e.q. 4)		0.025	0.108	1.341	1.00e-06
Weighted outdegree	"Prestige", scores measuring HQ a country hosts (see e.q. 4)		0.025	0.154	1.392	0
Eigenvector	"Authority", scores measuring relative ranking of connectedness taking into account the whole network (see e.q. 5)		0.249	0.221	1	0.018
Betweenness	"Gateway", scores measuring the number of shortest paths from all countries to all others through a given country (see e.q. 6)		0.0004	0.001	0.011	0
Closeness	"Propinquity", scores measuring the average shortest distance length between a country and all other countries in a network (see e.q. 7)		0.076	0.215	0.844	0
Economic factor	GDP per capita in 2021 (USD)		17,309.63	23,242.76	133,590.1	221.158
Energy policy instrument	Dummy variable: 1 if a country has at least one related policy in effect in 2021, or 0 otherwise		0.792	0.408	1	0
Government's administrative capacity	Scores measuring regulatory quality and government effectiveness in a given country		2.541	0.948	4.761	0.313

adopter can still be influenced by networks due to its connectedness with influential counterparts.

In conclusion, the sustainable innovation capacities of MNCs and their strategies for global expansion result in countries assuming varying roles in transnational CCMT diffusion. Throughout this process, leading countries, notably the US, Germany, and Japan, control the majority of network resources, leaving others in a relatively disadvantaged position. The disparities in countries' network capital allow us to investigate whether these network advantages can indeed facilitate the development of CCMTs.

5.2. Econometric regression results

Table 5 presents the estimated results concerning the relationship between network capital and CCMT development. Given that different network measures conceptually capture different facets of network capital, they are introduced separately into the econometric models. This mitigates issues related to over-identification and multicollinearity issues (Shi et al., 2022). Consequently, we estimate six separate econometric regression models, each emphasizing a single network capital.

Regarding the linkage volume variables, both weighted total degree and weighted indegree show a statistically significant positive relationship with renewable electricity production at the 5% level. Additionally, weighted outdegree demonstrates significance at the 10% level. These results suggest that a country's CCMT development can be positively influenced by the presence of sustainable innovative MNCs (Antras et al., 2009).

The significant estimate of the coefficient of weighted indegree suggests that recipient countries benefit from receiving subsidiaries of MNCs with advanced CCMT capacities. This finding may be attributed to the substantial consumer markets for certain CCMTs in less developed countries, such as China and Brazil. Considering that countries hosting MNCs' headquarters tend to be more developed than countries receiving subsidiaries (Pfeiffer and Mulder, 2013), driven by market and return-on-investment interests, MNCs actively promote innovations originating in countries where their headquarters are located to other nations through their globally deployed subsidiaries (Caleb et al., 2021).

Another plausible explanation is the latecomer advantages in recipient countries, where less developed countries can rapidly adopt innovative technologies across their industrial structures (Perkins and Neumayer, 2005). First, late industrializers reap advantages from learning from technological pioneers (Grubler, 2012). The initial R&D phase of CCMT development typically involves high cost, limited flexibility, and unpredictability. Risk-taking MNCs tend to drive down application costs, enhance performance, and render the technologies economically viable, albeit at the cost of substantial expenditures (Hoskisson et al., 2011). Second, governments in advanced economies have been actively pursuing policies aimed at accelerating the adoption of emerging CCMTs such as residential solar photovoltaics and electric vehicles. Latecomer nations can leverage the experience and effective policies of these forerunners to accelerate the proliferation rates of such technologies. Fadly and Fontes (2019) and Lopolito et al. (2022) demonstrate the positive cross-country spillover effects stemming from policies designed to accelerate the development of CCMTs. Moreover, considering that most recipient countries have not yet established substantial capacity in this domain, they have the flexibility to choose and integrate new technologies as part of their capital expansion efforts (Bank, 1992; Popp, 2020).

The significant coefficient estimate for weighted outdegree suggests that a country can benefit from hosting the headquarters of MNCs with advanced CCMT capacities. Several arguments explain this finding. First, technologies tend to spread from their origins and initial markets due to geographical proximity (Corradini et al., 2021; Ernst, 2002). Face-to-face interactions, which decay with distance increases, further expedite this diffusion process (Bahar et al., 2014). Therefore, countries hosting the headquarters of these MNCs gain early access, allowing them to adopt advanced CCMTs before widespread commercialization (Aldieri, 2011). Moreover, domestic diffusion of new technologies typically face fewer policy and regulatory barriers compared to transnational diffusion (Rao and Kishore, 2010). For instance, concerns over intellectual property rights can be more manageable when technologies are disseminated within a country, as opposed to cross-border transfers with varying intellectual property regulations (Dechezleprêtre and

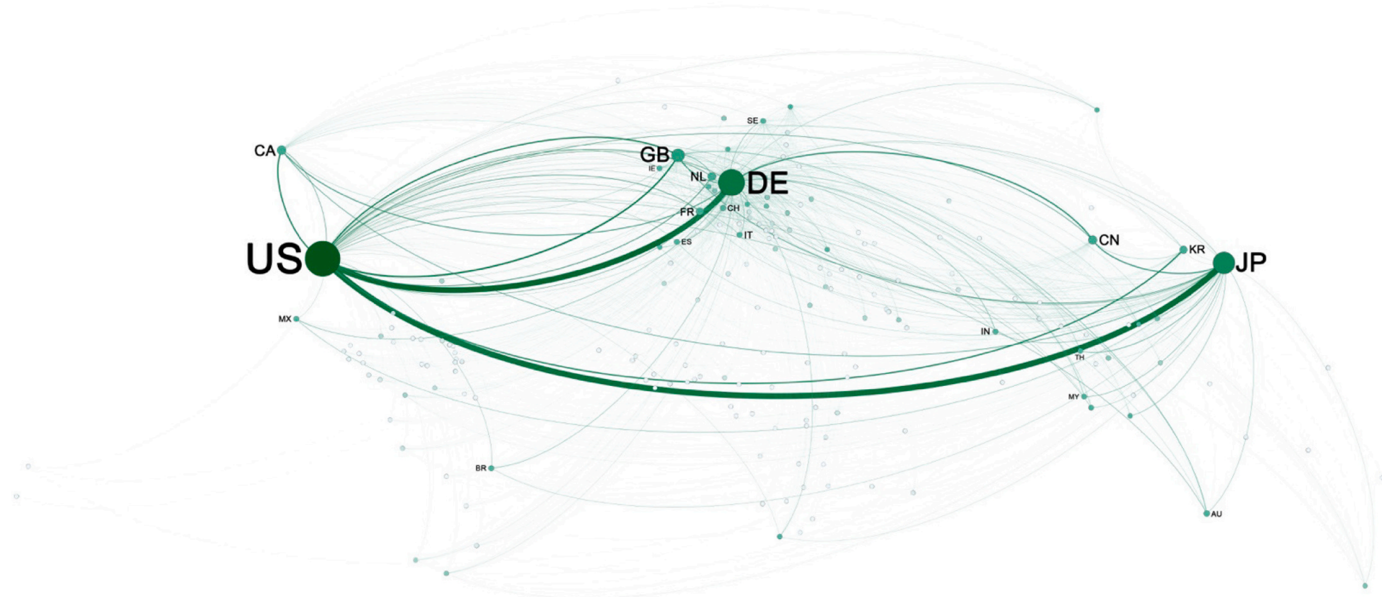


Fig. 3. Global CCMT diffusion network based on weighted total degree.

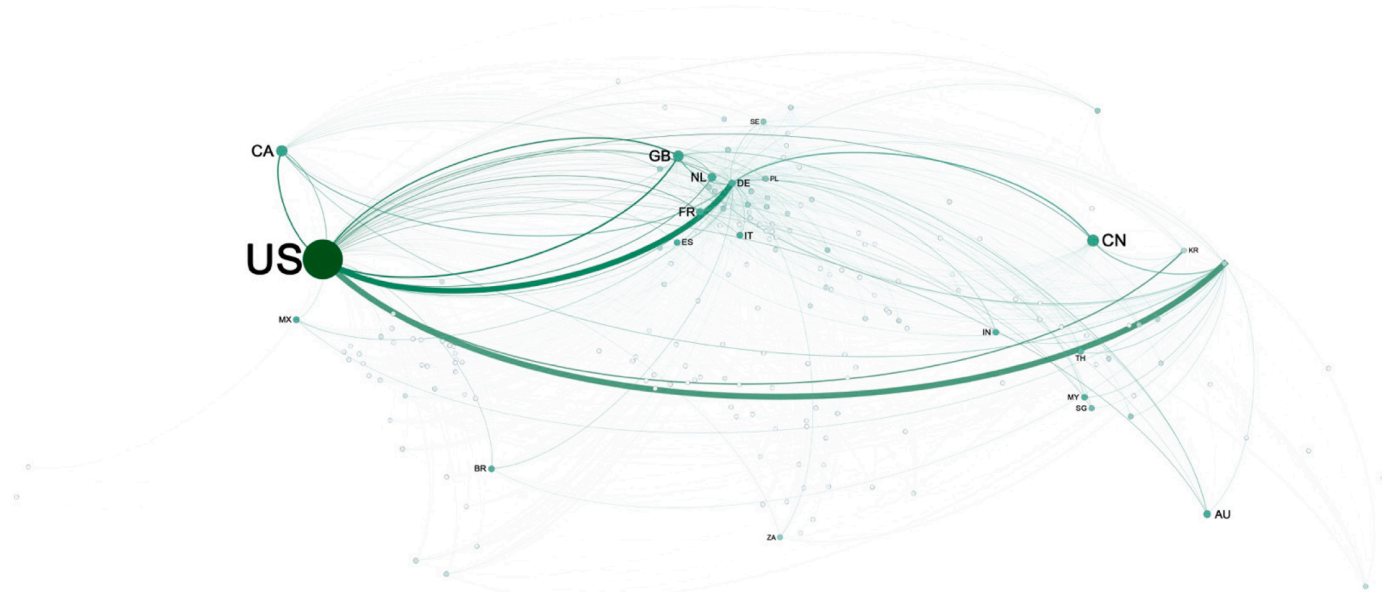


Fig. 4. Global CCMT diffusion network based on weighted indegree.

Glachant, 2014; Popp, 2020). Consequently, both geographic and institutional proximity to innovators serve as effective and efficient means for disseminating knowledge.

Regarding structural positionalities, all three measurements, namely eigenvector, closeness, and betweenness, are identified as important factors affecting renewable electricity production. This supports the argument that an economy, which may not be the primary source or recipient of CCMTs in terms of quantity, can still derive benefits from innovators thanks to its pivotal position within the network (Fadly and Fontes, 2019; Vega and Mandel, 2018).

Structural proximity to other innovators within the networks confers two significant network advantages that facilitate CCMT development in the intermediate countries. First, central positioning in various capital flows provides these economies with access to a diverse range of resources, capabilities, and markets (Lin, 2011). This creates great opportunities for knowledge sharing and learning (Cheng, 2022). Such opportunities are strategically valuable, enabling economies to acquire new technologies ahead of widespread adoption. Second, their hub and gateway positions allow for the convergence of interdisciplinary knowledge, effectively transforming these economies into "chemical containers" where various innovations intersect (Penco, 2015). Within these economies, entities such as firms and governments do not merely act as passive knowledge recipients but also function as knowledge processors through local market exploration. Throughout these processes, network synergy facilitates knowledge reproduction, drawing from a broad pool of information initially held by each individual agent (Bathelt and Cohendet, 2014; Bathelt et al., 2004). This is particularly crucial in the context of CCMTs, which can be regarded as radical

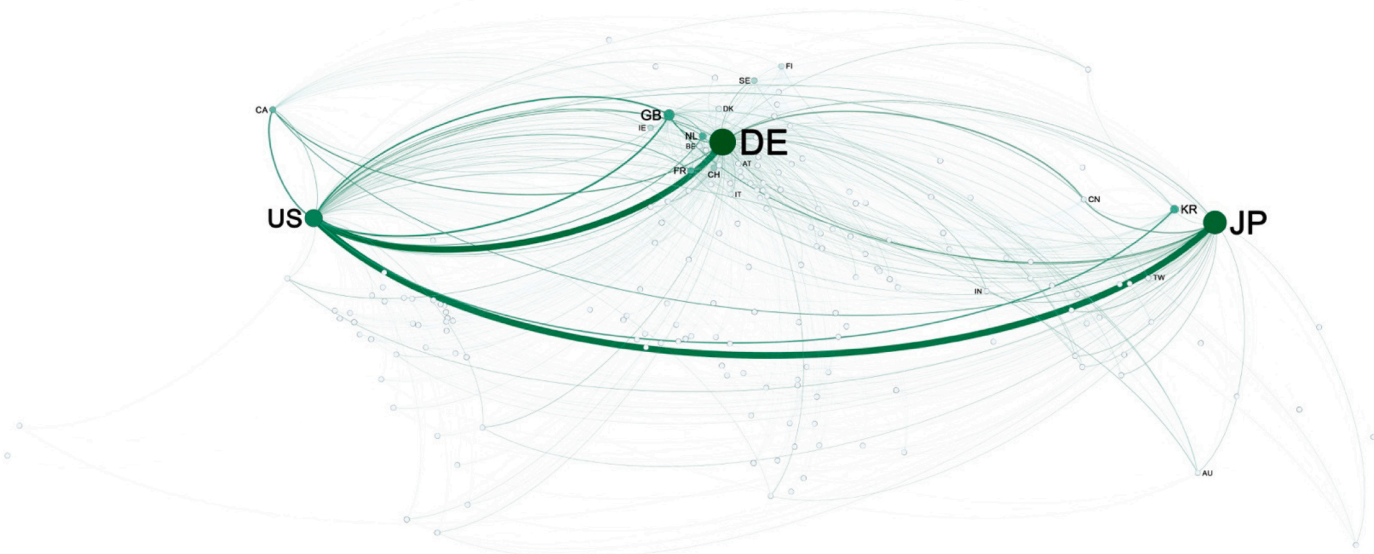


Fig. 5. Global CCMT diffusion network based on weighted outdegree.

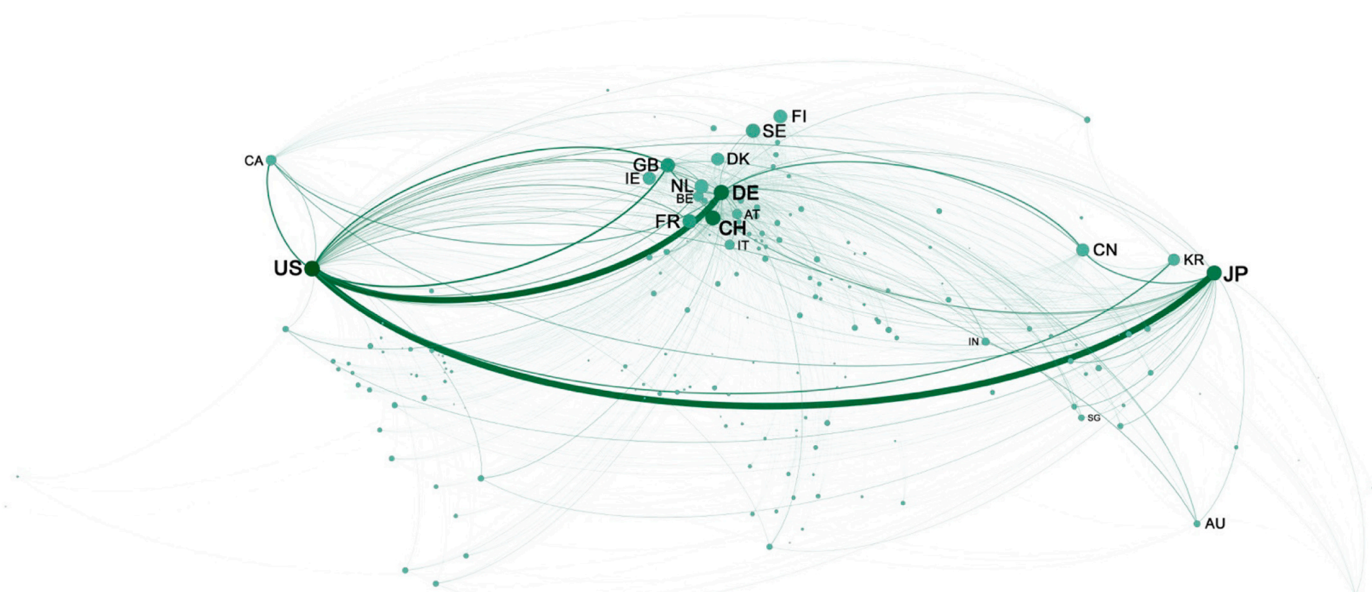


Fig. 6. Global CCMT technology diffusion network based on eigenvector.

innovations emerging from the synthesis of existing technologies in novel ways (Li et al., 2020).

In the CCMT diffusion network, these MNCs can adapt their international investment strategies through interactions with local stakeholders. Simultaneously, regional policymakers can leverage network capital generated by participating in MNCs' global expansion to drive regional development. This point can be further highlighted with the use of an illustrative example. In particular, we can consider BYD, a Shenzhen-based Chinese company that has established three factories in Brazil to domestically produce chassis and batteries for electric buses, and solar panels. In 2015, BYD initiated its operations in Campinas, Brazil, manufacturing chassis for electric buses. In 2017, the Brazilian Development Bank introduced a new policy known as FINAME, aimed at enhancing local manufacturer competitiveness and sustain national supply chains. Under this policy, customers seeking financial loans were required to ensure that the nationalization index of the products they purchase reached a minimum of 50%. In response, BYD established another factory in Manaus to produce lithium iron phosphate batteries locally. These batteries, which were previously imported, are now manufactured to supply the electric buses assembled in Campinas. In addition to localizing production, BYD also consolidates its R&D efforts locally, collaborating with local universities and research institutes to adapt its technologies to Brazil's local conditions and requirements. This collaborative approach allows BYD to access and incorporate existing local technological competencies, fostering synergy with the local technological ecosystem.[10]

In this case, Brazil benefits in various ways from participating in the

[10] For a more detail discussion, please refer to https://carnegieendowment.org/2022/10/18/why-brazil-sought-chinese-investments-to-diversify-its-manufacturing-economy-pub-88194

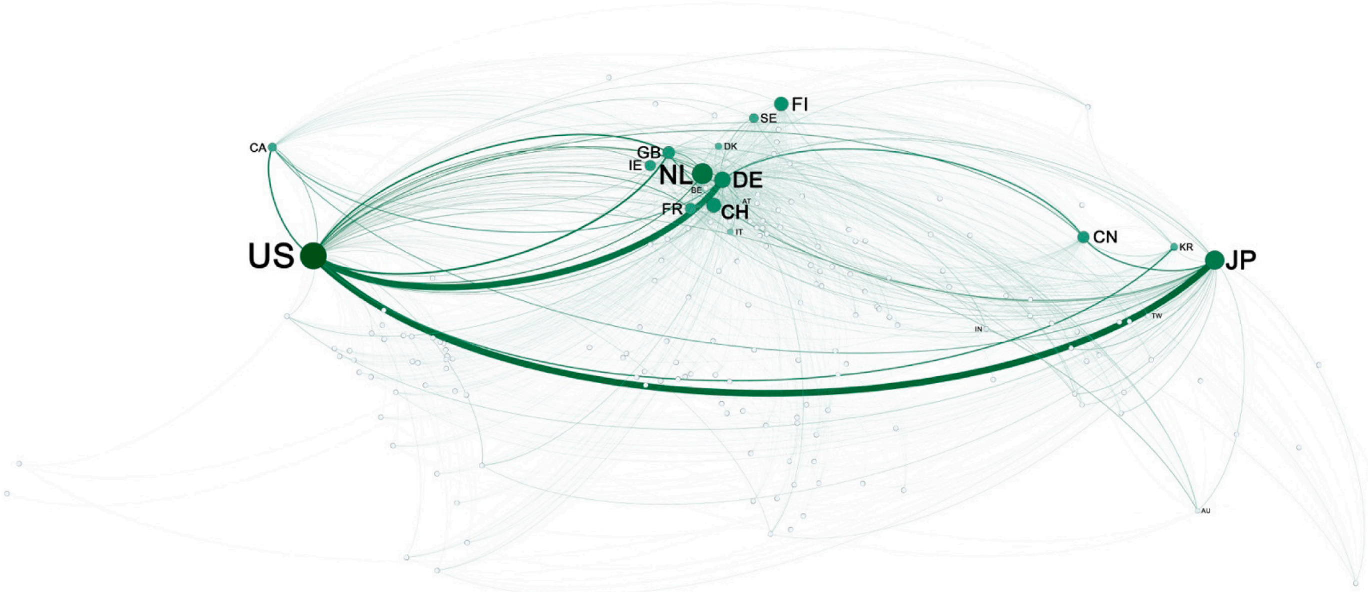


Fig. 7. Global CCMT technology diffusion network based on betweenness.

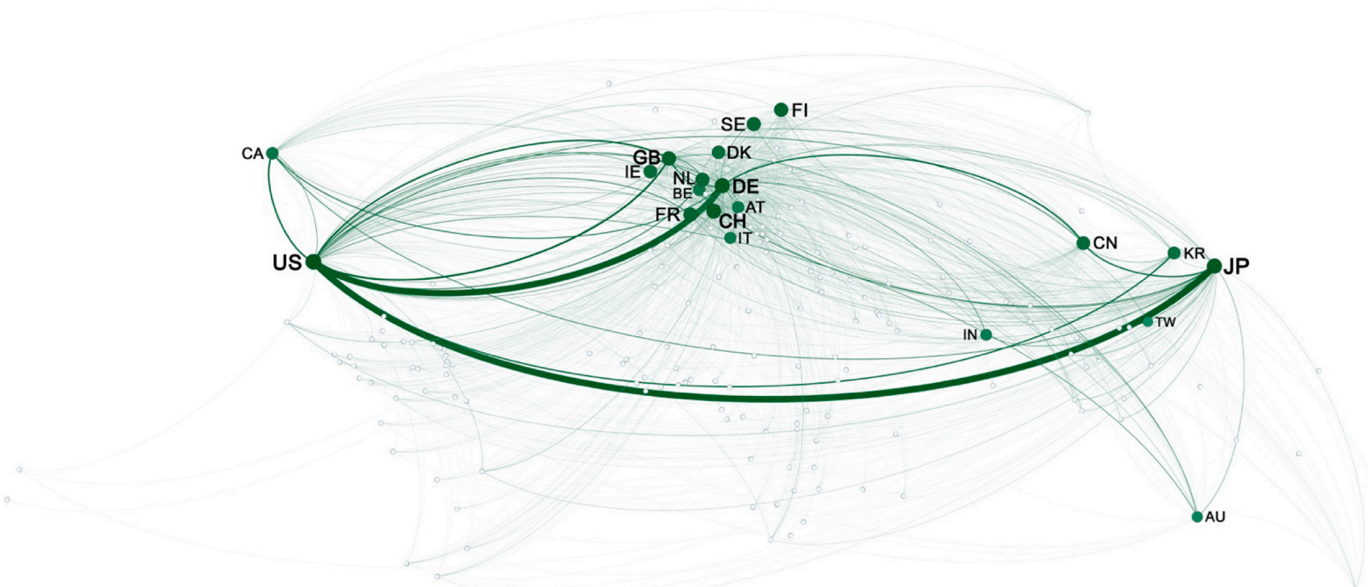


Fig. 8. Global CCMT technology diffusion network based on closeness.

Table 4
Top 10 countries by network capital.

Linkage volume						Structural positionalities						Directed pairs	
Weighted total degree		Weighted indegree		Weighted outdegree		Eigenvector		Betweenness		Closeness			
US	2.155	US	1.341	DE	1.392	US	1	US	0.0109	US	0.844	JP – US	0.493
DE	1.48	CN	0.28	JP	1.175	DE	0.969	NL	0.0078	JP	0.793	DE – US	0.472
JP	1.204	CA	0.258	US	0.813	CH	0.965	JP	0.0071	DE	0.793	UK – US	0.132
GB	0.594	GB	0.24	GB	0.354	JP	0.956	DE	0.0056	CH	0.786	US – CA	0.112
CA	0.311	NL	0.137	KR	0.191	GB	0.91	CH	0.0049	GB	0.736	US – UK	0.11
CN	0.282	AU	0.122	NL	0.125	FR	0.905	FI	0.0046	FR	0.724	DE – CN	0.105
NL	0.261	FR	0.12	FR	0.088	SE	0.89	GB	0.0038	FI	0.716	KR – US	0.097
KR	0.232	DE	0.088	CA	0.053	NL	0.876	CN	0.0035	SE	0.71	JP – CN	0.094
FR	0.208	IN	0.075	CH	0.033	FI	0.86	FR	0.0032	NL	0.702	DE – CA	0.066
AU	0.122	IT	0.073	SE	0.025	CN	0.815	IE	0.0031	CN	0.676	DE – CA	0.057

Table 5
Regression results ($n = 173$).

Variable	Dependent variable: Log renewable electricity production per capita					
	1	2	3	4	5	6
Weighted total degree (log)	0.142**					
	(0.063)					
Weighted indegree (log)		0.147**				
		(0.065)				
Weighted outdegree (log)			0.086*			
			(0.046)			
Eigenvector (log)				0.478***		
				(0.177)		
Closeness (log)					0.070**	
					(0.035)	
Betweenness (log)						0.131**
						(0.063)
GDP per capita (log)	0.325**	0.329**	0.389**	0.308*	0.385**	0.378**
	(0.158)	(0.158)	(0.152)	(0.156)	(0.152)	(0.152)
Policy support (dummy)	0.527	0.519	0.793**	0.410	0.790**	0.791**
	(0.383)	(0.385)	(0.365)	(0.390)	(0.364)	(0.364)
Government's administrative capacity (log)	0.907*	0.919*	0.816	0.891*	0.790	0.807
	(0.525)	(0.526)	(0.530)	(0.522)	(0.530)	(0.528)
Constant	−11.279	−11.281	−11.744	−11.031	−11.936	−11.040
Adjusted R-squared	0.305	0.304	0.298	0.313	0.300	0.301

Note: Standard error in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. We log-transform all the variables to produce normally distributed model residuals. Additionally, a small constant is added to variables with zero value before log-transform to address the presence of zeros in the dataset.

global electric vehicle production networks. First, local manufacturing of eco-friendly products like electric buses and cost-effective solar panels directly contributes to Brazil's emission reduction goals. Additionally, policies encouraging MNCs like BYD to source from local suppliers stimulate domestic manufacturing, foster learning, and facilitate innovation localization. Furthermore, active engagement in sustainable innovation networks can advance local industrial ecosystems, presenting Brazil with opportunities to be more integrated into knowledge-intensive supply chains (Hiratuka, 2022).

Regarding the control variables, countries with stronger economic performance are more inclined to generate electricity from renewable resources, which align with previous research on clean technology diffusion. Given that CCMT development requires significant inputs of human capital and financial resources, its development tends to be more feasible for economically prosperous nations. Additionally, the results indicate that countries that have implemented climate change mitigation policies tend to exhibit stronger performance in CCMT development. These policies not only reflect a country's commitment to environmental conservation and clean technology development, but also play a regulatory role in shaping the nation's industrial strategies and standards. Finally, the results indicate the positive impact of a government's administrative capacity in fostering CCMT development, emphasizing the crucial role of a supportive regulatory environment in driving progress in this field.

6. Conclusion

Given the magnitude of the sustainability target flux, current literature and policy debates place significant emphasis on the role of CCMTs in achieving net-zero carbon emission goals. In this paper, we contribute to this discussion by constructing the global diffusion networks of CCMTs and assessing the impact of network capital on CCMT development. We argue that, beyond domestic factors, a country's progress in CCMT development is also influenced by various forms of network capital embedded within the global CCMT diffusion networks. Our findings demonstrate that countries, that establish stronger connections with global CCMT diffusion networks through sustainable innovative MNCs, tend to exhibit superior performance in CCMT development.

Specifically, we first identified the top 228 sustainable innovation MNCs using CCMT-related patent data up to and including the year 2021. Next, we constructed the global CCMT diffusion networks represented by weighted intra-firm networks of these 228 MNCs. These networks took into account several factors, including the number of MNCs a country hosts, the sustainable innovation capacities of these MNCs, as well as their business scales. Subsequently, we quantified various aspects of network capital for each country within these networks with respect to linkage volumes and structural positionalities. Finally, we incorporated these network capital measures into the econometric regression models to investigate the extent to which network capital may influence CCMT development on a national level.

Among the key findings, the network statistical analysis reveals a global disproportionate pattern of CCMT diffusion network, wherein only a small group of countries holds the majority of CCMT resources. Nonetheless, countries exhibited varying performance across different network capital metrics. Regarding the econometric regression outcomes, we identified positive effects associated with various forms of network capital, highlighting the pivotal role of transnational technology diffusion in advancing CCMT development.

Our findings have several important policy implications. First, a country's CCMT development benefits from the presence of sustainable innovation MNCs, whether they host their headquarters or establish subsidiaries within the country. Consequently, policymakers should proactively seek to attract MNCs possessing strong innovation capacities in CCMTs. This can be achieved by incentive-based policies focused on attracting foreign investment in domestic clean technology innovation activities such as financial measures include tax benefits, grants, subsidies, and interest-reduced loans. These measures lower the costs associated with development projects and simultaneously mitigate the risks of foreign investment for MNCs. Meanwhile, governments can also establish investment promotion agencies to assist MNCs with location selection, talent recruitment, and financing. Moreover, countries can increase their appeal by fostering a regulatory environment that encourages competition, protects intellectual property rights, and simplifies business registration process. Such favorable regulations can boost MNCs' confidence and alleviate concerns related to cross-border technology transfer.

In addition to incentive-based policies, countries can also leverage capacity-building strategies to enhance their competitiveness in attracting CCMT-related investment. First, nations can identify their existing technological and knowledge strengths to prioritize the development of certain CCMT industries. Simultaneously, investments in infrastructure, higher education, public services, and amenities that are necessary for CCMT innovation activities should be made. This strengthens the country's expertise in these technologies and fosters international collaborations with MNCs. Furthermore, besides developing technologies directly belonging to CCMTs, countries can explore their existing capacities that are relevant to CCMTs. Enhancing these related capacities facilitates them to enter new specializations within the CCMT domains. To leverage on network capital, policymakers can employ network analysis, as demonstrated in this paper, to precisely identify their countries' global positions within the CCMT diffusion networks. This involve assessing existing MNC investment, available international capital, and connections with other countries through these MNCs. Once existing capacities as well as international linkages are identified, policymakers can strategically focus on developing these complementary capacities.

Third, the findings highlight the potential for intermediary countries to acquire valuable relational assets due to their structural proximity to other key CCMT innovators. These intermediary countries, positioned as hubs and gateways within the diffusion networks, are well-placed to benefit from knowledge flows and information exchanges, functioning as hubs where interdisciplinary knowledge converge. This is primarily because MNCs need to engage with diverse local stakeholders when exploring new markets. Such collaborative engagement not only facilitates knowledge dissemination from headquarters to the subsidiary locations but also stimulates the generation of new knowledge as technologies are adapted to local contexts. In this regard, policymakers should consider establishing various communication platforms, such as regular conventions and incubators. These platforms can effectively facilitate interactions among different stakeholders and sectors, fostering an environment where various forms of knowledge synergize.

There are several limitations in our study. First, we measured CCMT diffusion using intra-firm relationships which did not consider knowledge exchanges and spillovers between firms. Future studies could incorporate indicators capturing inter-firm relationships like mergers and acquisitions, and joint ventures to measure the strength of knowledge flows between companies. Second, our analysis was conducted at the national level. Yet, within a single country, there can be significant regional disparities in CCMT development, spatial concentrations of MNCs, industrialization levels, and industrial strategies. Conducting studies at finer spatial scales can provide a deeper insight into this regional heterogeneity, allowing for more locally tailored policy recommendations that can address the unique contextual challenges and opportunities within each region. Third, we employed CCMT-related patent data up until and including 2021 to identify sustainable innovation MNCs. However, our analysis relied solely on corporate ownership and the geographical information of these MNCs' headquarters and subsidiaries as of 2021. This failed to account for changes that might have occurred during the study period, including those that might have influenced network capital calculation. Changes in corporate ownership, such as mergers and acquisitions, and restructuring can significantly impact a company's innovation strategies and practices within the CCMT domain. Moreover, we examined the entire patent category Y02/Y04S without differentiating across its nine sub-classifications. Different CCMTs may exhibit distinct diffusion dynamics due to factors like market demand and technological complexity. Future studies can investigate individual sub-classifications within CCMTs to gain deeper insights into the global landscape of sustainable innovation and inform targeted strategies for promoting the diffusion of specific CCMTs. Finally, this study utilized the network as an outcome for nodal-level analysis. Future research could investigate the formation and evolution of networks using models such as the exponential random graph model. These models facilitate the simultaneous modeling of the endogenous structural characteristics of a network along with the impact of exogenous variables.

CRediT authorship contribution statement

Jianhua Zhang: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Dimitris Ballas:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **Xiaolong Liu:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization.

Acknowledgements

We thank the two reviewers, editor, co-editor, and Roelant Heule for their helpful feedback and contributions.

Appendix A. Countries or regions included in this analysis

Country/ region	Country/ region code	Outgoing linkages	Incoming linkages	Number of CCMT-related patents
Afghanistan	AF	0	2	0
Albania	AL	0	15	0
Algeria	DZ	0	68	0
Andorra *	AD	0	1	0
Angola	AO	0	29	0
Antigua and Barbuda	AG	0	2	0
Argentina	AR	0	304	0
Armenia	AM	0	4	0
Aruba	AW	0	2	0
Australia	AU	1	1,891	25
Austria	AT	3	476	617
Azerbaijan	AZ	0	19	0
Bahrain	BH	0	24	0
Bangladesh	BD	0	43	0
Barbados	BB	0	34	0
Belarus	BY	0	28	0
Belgium	BE	2	566	892
Benin	BJ	0	11	0
Bermuda *	BM	0	183	0
Bhutan	BT	0	1	0

(continued on next page)

(*continued*)

Country/ region	Country/ region code	Outgoing linkages	Incoming linkages	Number of CCMT-related patents
Bolivia	BO	0	20	0
Bosnia and Herzegovina	BA	0	51	0
Botswana	BW	0	27	0
Brazil	BR	0	1,135	0
British Virgin Islands	VG	0	90	0
Brunei	BN	0	13	0
Bulgaria	BG	0	137	0
Burkina Faso	BF	0	9	0
Burundi	BI	0	1	0
Cambodia	KH	0	23	0
Cameroon	CM	0	15	0
Canada	CA	4	3,075	1,778
Cape Verde	CV	0	3	0
Cayman Islands	KY	0	176	0
Chad	TD	0	2	0
Chile	CL	0	303	0
China Mainland	CN	6	4,455	3,255
Colombia	CO	0	238	0
Costa Rica	CR	0	73	0
Croatia	HR	0	120	0
Cuba	CU	0	4	0
Curaçao *	CY	0	34	0
Cyprus	CW	0	19	0
Czech Republic	CZ	0	376	0
Democratic Republic of the Congo	CD	0	14	0
Denmark	DK	3	380	1,985
Djibouti	DJ	0	2	0
Dominica	DM	0	5	0
Dominican Republic	DO	0	33	0
Ecuador	EC	0	70	0
Egypt	EG	0	204	0
El Salvador	SV	0	30	0
Equatorial Guinea	GQ	0	1	0
Eritrea	ER	0	2	0
Estonia	EE	0	85	0
Ethiopia	ET	0	5	0
Federated States of Micronesia *	FJ	0	2	0
Fiji	FO	0	1	0
Finland	FI	3	278	1,237
France	FR	10	1,475	6,077
Gabon	GA	0	9	0
Gambia *	GM	0	3	0
Georgia	GE	0	11	0
Germany	DE	26	2,213	22,967
Ghana	GH	0	39	0
Gibraltar *	GI	0	20	0
Greece	GR	0	212	0
Guatemala	GT	0	59	0
Guinea	GN	0	10	0
Guyana	GY	0	1	0
Haiti	HT	0	1	0
Honduras	HN	0	23	0
Hong Kong SAR, China	HK	0	649	0
Hungary	HU	0	301	0
Iceland	IS	0	11	0
India	IN	1	986	155
Indonesia	ID	0	492	0
Iran	IR	0	34	0
Iraq	IQ	0	14	0
Ireland	IE	3	535	1,570
Israel	IL	0	219	0
Italy	IT	1	1,068	129
Ivory Coast *	CI	0	24	0
Jamaica	JM	0	8	0
Japan	JP	77	541	46,529
Jordan	JO	0	17	0
Kazakhstan	KZ	0	67	0
Kenya	KE	0	76	0
Kosovo	XK	0	5	0
Kuwait	KW	0	10	0
Kyrgyzstan	KG	0	1	0
Laos	LA	0	7	0
Latvia	LV	0	61	0
Lebanon	LB	0	26	0
Lesotho	LS	0	1	0
Liberia	LR	0	10	0

(*continued on next page*)

(*continued*)

Country/ region	Country/ region code	Outgoing linkages	Incoming linkages	Number of CCMT-related patents
Libya	LY	0	2	0
Liechtenstein *	LI	0	6	0
Lithuania	LT	0	66	0
Luxembourg	LU	0	488	0
Macao SAR, China	MO	0	7	0
Macedonia	MK	0	32	0
Madagascar	MG	0	7	0
Malawi	MW	0	6	0
Malaysia	MY	0	808	0
Mali	ML	0	4	0
Malta	MT	0	49	0
Marshall Islands *	MH	0	62	0
Mauritania	MR	0	2	0
Mauritius	MU	0	51	0
Mexico	MX	0	1,163	0
Moldova	MD	0	7	0
Monaco *	MC	0	3	0
Mongolia	MN	0	7	0
Montenegro	ME	0	17	0
Morocco	MA	0	164	0
Mozambique	MZ	0	27	0
Myanmar	MM	0	45	0
Namibia	NA	0	32	0
Nepal	NP	0	1	0
Netherlands	NL	7	1,702	4,631
New Zealand	NZ	0	235	0
Nicaragua	NI	0	18	0
Niger	NE	0	1	0
Nigeria	NG	0	86	0
Norway	NO	0	330	0
Oman	OM	0	37	0
Pakistan	PK	0	70	0
Palestine	PW	0	1	0
Panama	PA	0	128	0
Papua New Guinea	PG	0	22	0
Paraguay	PY	0	26	0
Peru	PE	0	129	0
Philippines	PH	0	335	0
Poland	PL	0	606	0
Portugal	PT	0	412	0
Qatar	QA	0	35	0
Republic of Serbia	RS	0	121	0
Republic of the Congo	CG	0	10	0
Romania	RO	0	270	0
Russia	RU	0	555	0
Rwanda	RW	0	6	0
San Marino *	SM	0	4	0
Saint Kitts and Nevis	KN	0	1	0
Saint Lucia	LC	0	7	0
Saint Vincent and the Grenadines	VC	0	2	0
Samoa	WS	0	6	0
Saudi Arabia	SA	0	188	0
Senegal	SN	0	22	0
Seychelles	SC	0	3	0
Sierra Leone	SL	0	2	0
Singapore	SG	0	943	0
Slovakia	SK	0	234	0
Slovenia	SI	0	120	0
Solomon Islands	SB	0	1	0
South Africa	ZA	0	540	0
South Korea	KR	11	647	12,639
Spain	ES	0	1,010	0
Sri Lanka	LK	0	38	0
Sudan	SD	0	5	0
Suriname	SR	0	1	0
Swaziland	SZ	0	5	0
Sweden	SE	5	620	2,485
Switzerland	CH	5	637	2,224
Syria	SY	0	4	0
Taiwan, China	TW	1	401	75
Thailand	TH	0	906	0
The Bahamas	BS	0	58	0
Togo	TG	0	5	0
Tonga *	TO	0	1	0
Trinidad and Tobago	TT	0	29	0
Tunisia	TN	0	85	0

(*continued on next page*)

(*continued*)

Country/ region	Country/ region code	Outgoing linkages	Incoming linkages	Number of CCMT-related patents
Turkey	TR	0	465	0
Uganda	UG	0	11	0
Ukraine	UA	0	259	0
United Arab Emirates	AE	0	298	0
United Kingdom	GB	8	3,600	4,474
United Republic of Tanzania	TZ	0	40	0
United States of America	US	51	21,637	31,972
Uruguay	UY	0	109	0
Uzbekistan	UZ	0	14	0
Venezuela	VE	0	135	0
Vietnam	VN	0	340	0
Zambia	ZM	0	22	0
Zimbabwe	ZW	0	28	0

[*] Countries/regions included in statistical network analysis but excluded from econometric regression analysis.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2024.107497.

References

Abdul Wahab, S., Rose, R.C., Kumar, N., Uli, J., 2009. A review on the effects of inter-firm technology transfer characteristics and degree of technology transfer. Eur. J. Soc. Sci. 8 (2), 297–309.
Aguirre, M., Ibikunle, G., 2014. Determinants of renewable energy growth: a global sample analysis. Energy Policy 69, 374–384.
Alderson, A.S., Beckfield, J., 2004. Power and position in the world city system. Am. J. Sociol. 109 (4), 811–851.
Aldieri, L., 2011. Technological and geographical proximity effects on knowledge spillovers: evidence from the US patent citations. Econ. Innov. New Technol. 20 (6), 597–607.
Aldieri, L., Carlucci, F., Vinci, C.P., Yigitcanlar, T., 2019. Environmental innovation, knowledge spillovers and policy implications: a systematic review of the economic effects literature. J. Clean. Prod. 239, 118051.
Allan, C., Jaffe, A.B., Sin, I., 2014. Diffusion of green technology: a survey.
Allen, M.R., Friedlingstein, P., Girardin, C.A., Jenkins, S., Malhi, Y., Mitchell-Larson, E., Peters, G.P., Rajamani, L., 2022. Net zero: science, origins, and implications. Annu. Rev. Environ. Resour. 47, 849–887.
Angelucci, S., Hurtado-Albir, F.J., Volpe, A., 2018. Supporting global initiatives on climate change: The EPO's "Y02-Y04S" tagging scheme. World Patent Inf. 54, S85–S92.
Antonelli, C., Krafft, J., Quatraro, F., 2010. Recombinant knowledge and growth: the case of ICTs. Struct. Chang. Econ. Dyn. 21 (1), 50–69.
Antras, P., Desai, M.A., Foley, C.F., 2009. Multinational firms, FDI flows, and imperfect capital markets. Q. J. Econ. 124 (3), 1171–1219.
Archibugi, D., Filippetti, A., 2018. The retreat of public research and its adverse consequences on innovation. Technol. Forecast. Soc. Chang. 127, 97–111.
Arora, N.K., Mishra, I., 2021. COP26: more challenges than achievements. Springer, pp. 1–4.
Athreye, S., Batsakis, G., Singh, S., 2016. Local, global, and internal knowledge sourcing: The trilemma of foreign-based R&D subsidiaries. J. Bus. Res. 69 (12), 5694–5702.
Athreye, S., Kathuria, V., Martelli, A., Piscitello, L., 2023. Intellectual property rights and the international transfer of climate change mitigating technologies. Res. Policy 52 (9), 104819.
Bahar, D., Hausmann, R., Hidalgo, C.A., 2014. Neighbors and the evolution of the comparative advantage of nations: evidence of international knowledge diffusion? J. Int. Econ. 92 (1), 111–123.
Baldwin, E., Carley, S., Brass, J.N., MacLean, L.M., 2017. Global renewable electricity policy: a comparative policy analysis of countries by income status. J. Compar. Policy Analys. Res. Pract. 19 (3), 277–298.
Bank, W., 1992. World development report 1992: development and the environment. The World Bank.
Bathelt, H., Cohendet, P., 2014. The creation of knowledge: local building, global accessing and economic development—toward an agenda. J. Econ. Geogr. 14 (5), 869–882.
Bathelt, H., Malmberg, A., Maskell, P., 2004. Clusters and knowledge: local buzz, global pipelines and the process of knowledge creation. Prog. Hum. Geogr. 28 (1), 31–56.
Beaverstock, J.V., Smith, R.G., Taylor, P.J., 2000. World-city network: a new metageography?.
Best, R., 2017. Switching towards coal or renewable energy? The effects of financial capital on energy transitions. Energy Econ. 63, 75–83.
Boschma, R., Coenen, L., Frenken, K., Truffer, B., 2018. Towards a theory of regional diversification: Combining insights from evolutionary economic geography and transition studies. In: Transitions in Regional Economic Development. Routledge, pp. 55–81.
Bosetti, V., Carraro, C., Massetti, E., Tavoni, M., 2008. International energy R&D spillovers and the economics of greenhouse gas atmospheric stabilization. Energy Econ. 30 (6), 2912–2929.
Caleb, H.T., Yim, C.K.B., Yin, E., Wan, F., Jiao, H., 2021. R&D activities and innovation performance of MNE subsidiaries: The moderating effects of government support and entry mode. Technol. Forecast. Soc. Chang. 166, 120603.
Carley, S., Baldwin, E., MacLean, L.M., Brass, J.N., 2017. Global expansion of renewable energy generation: an analysis of policy instruments. Environ. Resour. Econ. 68, 397–440.
Casson, M., Wadeson, N., 2018. Emerging market multinationals and internalisation theory. Int. Bus. Rev. 27 (6), 1150–1160.
Chaney, T., 2014. The network structure of international trade. Am. Econ. Rev. 104 (11), 3600–3634.
Chen, L., Msigwa, G., Yang, M., Osman, A.I., Fawzy, S., Rooney, D.W., Yap, P.-S., 2022. Strategies to achieve a carbon neutral society: a review. Environ. Chem. Lett. 20 (4), 2277–2310.
Cheng, H.W.J., 2022. Factors affecting technological diffusion through social networks: a review of the empirical evidence. World Bank Res. Obs. 37 (2), 137–170.
Chesbrough, H.W., 2003. Open innovation: The new imperative for creating and profiting from technology. Harvard Business Press.
Corradini, C., Santini, E., Vecciolini, C., 2021. The geography of Industry 4.0 technologies across European regions. Reg. Stud. 55 (10–11), 1667–1680.
De Beule, F., Van Beveren, I., 2019. Sources of open innovation in foreign subsidiaries: an enriched typology. Int. Bus. Rev. 28 (1), 135–147.
De Coninck, H., Sagar, A., 2015. Making sense of policy for climate technology development and transfer, vol. 15. Taylor & Francis, pp. 1–11.
Dechezleprêtre, A., Glachant, M., 2014. Does foreign environmental policy influence domestic innovation? Evidence from the wind industry. Environ. Resour. Econ. 58 (3), 391–413.
Denholm, P., Arent, D.J., Baldwin, S.F., Bilello, D.E., Brinkman, G.L., Cochran, J.M., Cole, W.J., Frew, B., Gevorgian, V., Heeter, J., 2021. The challenges of achieving a 100% renewable electricity system in the United States. Joule 5 (6), 1331–1352.
Derudder, B., 2012. International Handbook of Globalization and World Cities. Edward Elgar Publishing.
Derudder, B., 2021. Network analysis of 'urban systems': potential, challenges, and pitfalls. Tijdschr. Econ. Soc. Geogr. 112 (4), 404–420.
Derudder, B., Parnreiter, C., 2014. Introduction: the interlocking network model for studying urban networks: outline, potential, critiques, and ways forward. Tijdschr. Econ. Soc. Geogr. 105 (4), 373–386.
Diebold, F.X., Yılmaz, K., 2014. On the network topology of variance decompositions: measuring the connectedness of financial firms. J. Econ. 182 (1), 119–134.
Dunning, J.H., Lundan, S.M., 2008. Multinational Enterprises and the Global Economy. Edward Elgar Publishing.
EPO, 2023. Updates on Y02 and Y04S. https://www.epo.org/en/news-events/in-focus/classification/classification/updatesYO2andY04S.
EPO, E. P. O, 2021. Worldwide Patent Statistical Database (PATSTAT). (October).
Ernst, D., 2002. Global production networks and the changing geography of innovation systems. implications for developing countries. Econ. Innov. New Technol. 11 (6), 497–523.
Fadly, D., Fontes, F., 2019. Geographical proximity and renewable energy diffusion: an empirical approach. Energy Policy 129, 422–435.
Faems, D., Bos, B., Noseleit, F., Leten, B., 2020. Multistep knowledge transfer in multinational corporation networks: when do subsidiaries benefit from unconnected sister alliances? J. Manag. 46 (3), 414–442.
Ferraris, A., Santoro, G., Scuotto, V., 2020. Dual relational embeddedness and knowledge transfer in European multinational corporations and subsidiaries. J. Knowl. Manag. 24 (3), 519–533.
Ferrier, G.D., Reyes, J., Zhu, Z., 2016. Technology diffusion on the international trade network. J. Public Econ. Theory 18 (2), 291–312.

Freeman, L., 2004. The development of social network analysis. A Study in the Sociology of Science 1 (687), 159–167.
Furman, J.L., Porter, M.E., Stern, S., 2002. The determinants of national innovative capacity. Res. Policy 31 (6), 899–933.
Garsous, G., Worack, S., 2022. Technological expertise as a driver of environmental technology diffusion through trade: evidence from the wind turbine manufacturing industry. Energy Policy 162, 112799.
Gaur, A.S., Ma, H., Ge, B., 2019. MNC strategy, knowledge transfer context, and knowledge flow in MNEs. J. Knowl. Manag. 23 (9), 1885–1900.
Giuliani, E., Martinelli, A., Rabellotti, R., 2016. Is co-invention expediting technological catch up? A study of collaboration between emerging country firms and EU inventors. World Dev. 77, 192–205.
Grant, R., Phene, A., 2022. The knowledge based view and global strategy: past impact and future potential. Glob. Strateg. J. 12 (1), 3–30.
Grubler, A., 2012. Energy transitions research: Insights and cautionary tales. Energy Policy 50, 8–16.
Halleck-Vega, S., Mandel, A., Millock, K., 2018. Accelerating diffusion of climate-friendly technologies: A network perspective. Ecol. Econ. 152, 235–245.
Hansen, T., Coenen, L., 2015. The geography of sustainability transitions: review, synthesis and reflections on an emergent research field. Environ. Innov. Soc. Trans. 17, 92–109.
Hansen, U.E., Lema, R., 2019. The co-evolution of learning mechanisms and technological capabilities: Lessons from energy technologies in emerging economies. Technol. Forecast. Soc. Chang. 140, 241–257.
Harris, R., 2011. Models of regional growth: past, present and future. J. Econ. Surv. 25 (5), 913–951.
Heimeriks, G., Boschma, R., 2014. The path-and place-dependent nature of scientific knowledge production in biotech 1986–2008. J. Econ. Geogr. 14 (2), 339–364.
Herman, K.S., 2022. Beyond the UNFCCC North-South divide: How newly industrializing countries collaborate to innovate in climate technologies. J. Environ. Manag. 309, 114425.
Hidalgo, C.A., Balland, P.-A., Boschma, R., Delgado, M., Feldman, M., Frenken, K., Glaeser, E., He, C., Kogler, D.F., Morrison, A., 2018. The principle of relatedness. International conference on complex systems.
Hiratuka, C., 2022. Why Brazil Sought Chinese Investments to Diversify Its Manufacturing Economy. In: Carnegie Endowment for International Peace.
Hitt, M.A., Li, D., Xu, K., 2016. International strategy: from local to global and beyond. J. World Bus. 51 (1), 58–73.
Holm, J.R., Timmermans, B., Østergaard, C.R., Coad, A., Grassano, N., Vezzani, A., 2020. Labor mobility from R&D-intensive multinational companies: implications for knowledge and technology transfer. J. Technol. Transf. 45 (5), 1562–1584.
Horbach, J., Rammer, C., 2018. Energy transition in Germany and regional spill-overs: the diffusion of renewable energy in firms. Energy Policy 121, 404–414.
Hoskisson, R.E., Covin, J., Volberda, H.W., Johnson, R.A., 2011. Revitalizing entrepreneurship: the search for new research opportunities. J. Manag. Stud. 48 (6), 1141–1168.
Hotz-Hart, B., 2000. Innovation networks, regions, and globalization. In: The Oxford Handbook of Economic Geography, pp. 432–450.
Howells, J., 1996. Tacit knowledge. Tech. Anal. Strat. Manag. 8 (2), 91–106.
Huggins, R., Thompson, P., 2014. A network-based view of regional growth. J. Econ. Geogr. 14 (3), 511–545.
Huggins, R., Johnston, A., Thompson, P., 2012. Network capital, social capital and knowledge flow: how the nature of inter-organizational networks impacts on innovation. Ind. Innov. 19 (3), 203–232.
ICPP, 2023. AR6 Synthesis Report: Climate Change 2023. Summary for Policymakers.
IEA, 2021. Net zero by 2050: A roadmap for the global energy sector.
Jackson, M.O., Rogers, B.W., Zenou, Y., 2017. The economic consequences of social-network structure. J. Econ. Lit. 55 (1), 49–95.
Jaffe, A.B., Newell, R.G., Stavins, R.N., 2002. Environmental policy and technological change. Environ. Resour. Econ. 22 (1), 41–70.
Johnstone, N., Haščič, I., Popp, D., 2010. Renewable energy policies and technological innovation: evidence based on patent counts. Environ. Resour. Econ. 45 (1), 133–155.
Kaygusuz, K., 2012. Energy for sustainable development: a case of developing countries. Renew. Sust. Energ. Rev. 16 (2), 1116–1126.
Keller, W., 2004. International technology diffusion. J. Econ. Lit. 42 (3), 752–782.
Kim, J.E., 2020. Regulation trumps economics? Examining renewable energy policy, diffusion and investment in 80 developing countries. Energy Res. Soc. Sci. 70, 101613.
Kundur, P., Paserba, J., Ajjarapu, V., Andersson, G., Bose, A., Canizares, C., Hatziargyriou, N., Hill, D., Stankovic, A., Taylor, C., 2004. Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions. IEEE Trans. Power Syst. 19 (3), 1387–1401.
Li, D., Heimeriks, G., Alkemade, F., 2020. The emergence of renewable energy technologies at country level: relatedness, international knowledge spillovers and domestic energy markets. Ind. Innov. 27 (9), 991–1013.
Liebeskind, J.P., 2009. Knowledge, strategy, and the theory of the firm. In: Knowledge and Strategy. Routledge, pp. 197–219.
Lin, J.Y., 2011. New structural economics: a framework for rethinking development. World Bank Res. Obs. 26 (2), 193–221.
Liu, X., Derudder, B., 2012. Two-mode networks and the interlocking world city network model: A reply to Neal. Geogr. Anal. 44 (2), 171–173.
Lopolito, A., Falcone, P.M., Sica, E., 2022. The role of proximity in sustainability transitions: a technological niche evolution analysis. Res. Policy 51 (3), 104464.
Lusher, D., Koskinen, J., Robins, G., 2013. *Exponential random graph models for social networks: Theory, methods, and applications*. Cambridge University Press.
Mancusi, M.L., 2008. International spillovers and absorptive capacity: a cross-country cross-sector analysis based on patents and citations. J. Int. Econ. 76 (2), 155–165.
Mandel, A., Halleck Vega, S., Wang, D.-X., 2020. The contribution of technological diffusion to climate change mitigation: a network-based approach. Clim. Chang. 160, 609–620.
Markusen, J.R., 1995. The boundaries of multinational enterprises and the theory of international trade. J. Econ. Perspect. 9 (2), 169–189.
Martin, R., 2021. Path dependence and the spatial economy: putting history in its place. In: Handbook of Regional Science, pp. 1265–1287.
Monasterolo, I., Roventini, A., Foxon, T.J., 2019. Uncertainty of climate policies and implications for economics and finance: an evolutionary economics approach. Ecol. Econ. 163, 177–182.
Moss, T., 2009. Intermediaries and the Governance of Sociotechnical Networks in Transition. Environ. Plann. A: Econ. Space 41 (6), 1480–1495. https://doi.org/10.1068/a4116.
Nagaoka, S., 2009. Does strong patent protection facilitate international technology transfer? Some evidence from licensing contracts of Japanese firms. J. Technol. Transf. 34 (2), 128–144.
Neal, Z., Derudder, B., Liu, X., 2021. Using urban networks to gain new insight into old questions: Community, economy, bureaucracy. J. Urban Aff. 43 (1), 2–15.
Negro, S.O., Alkemade, F., Hekkert, M.P., 2012. Why does renewable energy diffuse so slowly? A review of innovation system problems. Renew. Sust. Energ. Rev. 16 (6), 3836–3846.
Nelson, R.R., Winter, S.G., 1982. The Schumpeterian tradeoff revisited. Am. Econ. Rev. 72 (1), 114–132.
Newman, M., 2018. Networks. Oxford University Press.
Nicolli, F., Vona, F., 2016. Heterogeneous policies, heterogeneous technologies: the case of renewable energy. Energy Econ. 56, 190–204.
Nicolli, F., Vona, F., 2019. Energy market liberalization and renewable energy policies in OECD countries. Energy Policy 128, 853–867.
Ockwell, D.G., Watson, J., MacKerron, G., Pal, P., Yamin, F., 2008. Key policy considerations for facilitating low carbon technology transfer to developing countries. Energy Policy 36 (11), 4104–4115.
Pegels, A., Altenburg, T., 2020. Latecomer development in a "greening" world: introduction to the Special Issue. World Dev. 135, 105084.
Penco, L., 2015. The development of the successful city in the knowledge economy: toward the dual role of consumer hub and knowledge hub. J. Knowl. Econ. 6 (4), 818–837.
Perkins, R., Neumayer, E., 2005. The international diffusion of new technologies: a multitechnology analysis of latecomer advantage and global economic integration. Ann. Assoc. Am. Geogr. 95 (4), 789–808.
Pfeiffer, B., Mulder, P., 2013. Explaining the diffusion of renewable energy technology in developing countries. Energy Econ. 40, 285–296.
Popp, D., 2020. International technology transfer, climate change, and the clean development mechanism. Rev. Environ. Econ. Policy 5 (1), 131–152.
Popp, D., Hascic, I., Medhi, N., 2011. Technology and the diffusion of renewable energy. Energy Econ. 33 (4), 648–662.
Probst, B., Touboul, S., Glachant, M., Dechezleprêtre, A., 2021. Global trends in the invention and diffusion of climate change mitigation technologies. Nat. Energy 6 (11), 1077–1086.
Przychodzen, W., Przychodzen, J., 2020. Determinants of renewable energy production in transition economies: a panel data approach. Energy 191, 116583.
Rai, V., Henry, A.D., 2016. Agent-based modelling of consumer energy choices. Nat. Clim. Chang. 6 (6), 556–562.
Rao, K.U., Kishore, V., 2010. A review of technology diffusion models with special reference to renewable energy technologies. Renew. Sust. Energ. Rev. 14 (3), 1070–1078.
Rodríguez-Pose, A., Crescenzi, R., 2008. Research and development, spillovers, innovation systems, and the genesis of regional growth in Europe. Reg. Stud. 42 (1), 51–67.
Sassen, S., 2013. The Global City. Princeton University Press, New York, London, Tokyo.
Shakeel, S.R., Takala, J., Zhu, L.-D., 2017. Commercialization of renewable energy technologies: a ladder building approach. Renew. Sust. Energ. Rev. 78, 855–867.
Shi, S., Wong, S.K., Zheng, C., 2022. Network capital and urban development: an inter-urban capital flow network analysis. Reg. Stud. 56 (3), 406–419.
Shih, H.-Y., Chang, T.-L.S., 2009. International diffusion of embodied and disembodied technology: A network analysis approach. Technol. Forecast. Soc. Chang. 76 (6), 821–834.
Spraggon, M., Bodolica, V., 2012. A multidimensional taxonomy of intra-firm knowledge transfer processes. J. Bus. Res. 65 (9), 1273–1282.
Taylor, P.J., 2001. Specification of the world city network. Geogr. Anal. 33 (2), 181–194.
Taylor, P.J., 2011. The interlocking network model. In: International Handbook of Globalization and World Cities. Edward Elgar Publishing.
Taylor, P.J., 2019. City generics: external urban relations in ancient-Mesopotamian and modern-global city networks. Urban Geogr. 40 (8), 1210–1230.
Taylor, P., Derudder, B., 2015. World City Network: A Global Urban Analysis. Routledge.
Vakulchuk, R., Overland, I., Scholten, D., 2020. Renewable energy and geopolitics: a review. Renew. Sust. Energ. Rev. 122, 109547.
Van Wijk, R., Jansen, J.J., Lyles, M.A., 2008. Inter-and intra-organizational knowledge transfer: a meta-analytic review and assessment of its antecedents and consequences. J. Manag. Stud. 45 (4), 830–853.
Veefkind, V., Hurtado-Albir, J., Angelucci, S., Karachalios, K., Thumm, N., 2012. A new EPO classification scheme for climate change mitigation technologies. World Patent Inf. 34 (2), 106–111.
Vega, S.H., Mandel, A., 2018. Technology diffusion and climate policy: a network approach and its application to wind energy. Ecol. Econ. 145, 461–471.

Verendel, V., 2023. Tracking artificial intelligence in climate inventions with patent data. Nat. Clim. Chang. 13 (1), 40–47.
Veugelers, R., 2012. Which policy instruments to induce clean innovating? Res. Policy 41 (10), 1770–1778.
Wall, R.S., Burger, M.J., Van der Knaap, G., 2011. The geography of global corporate networks: the poor, the rich, and the happy few countries. Environ. Plan. A 43 (4), 904–927.
Wang, F., Harindintwali, J.D., Yuan, Z., Wang, M., Wang, F., Li, S., Yin, Z., Huang, L., Fu, Y., Li, L., 2021. Technologies and perspectives for achieving carbon neutrality. The Innovation 2 (4), 100180.
Yeung, H.W.C., 2005. The firm as social networks: An organisational perspective. Growth Chang. 36 (3), 307–328.
Younas, A., 2021. Multinational Enterprises in Global Market Economy. Int. J. Dev. Public Policy 1 (7), 137–143.
Yu, H., Zhang, J., Zhang, M., Fan, F., 2022. Cross-national knowledge transfer, absorptive capacity, and total factor productivity: the intermediary effect test of international technology spillover. Tech. Anal. Strat. Manag. 34 (6), 625–640.
Zhang, J., Ballas, D., Liu, X., 2023. Neighbourhood-level spatial determinants of residential solar photovoltaic adoption in the Netherlands. Renew. Energy 206, 1239–1248.