PLOS SUSTAINABILITY AND TRANSFORMATION

RESEARCH ARTICLE

International alliances and technology diffusion: A worldwide analysis of adoption of energy, railway and satellite technologies

Michał Bączyk*, Koen Frenken, Matthijs B. Punt, Iris Wanzenböck

Copernicus Institute of Sustainable Development, Utrecht University, The Netherlands

* m.baczyk@uu.nl

Abstract

This study analyzes the role of international alliances in the adoption of new technology at the national level. We look at the worldwide diffusion of six key infrastructure technologies during the past six decades among 161 countries: nuclear power, solar power, wind power, marine power, high-speed rail, and telecommunication satellites. Acknowledging that international relations are not solely structured by formal alliances, we further investigate the impact of neighboring states on technology diffusion, as neighbors tend to maintain strong economic and cultural ties. We further look at simple imitation effects between states with similar political systems. With our focus on international alliances as drivers of international technology diffusion, our study complements economic studies on technology diffusion. For most of the technologies, we find evidence for spillovers between allied states as well as between neighboring states, while no such evidence was found for institutionally similar states. These results confirm the important role that international alliances may play in technology diffusion.

OPEN ACCESS

Citation: Bączyk M, Frenken K, Punt MB, Wanzenböck I (2024) International alliances and technology diffusion: A worldwide analysis of adoption of energy, railway and satellite technologies. PLOS Sustain Transform 3(6): e0000112. https://doi.org/10.1371/journal.pstr.0000112

Editor: Catherine Bale, University of Leeds Sustainability Research Institute, UNITED KINGDOM

Received: May 15, 2023

Accepted: April 8, 2024

Published: June 3, 2024

Peer Review History: PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: https://doi.org/10.1371/journal.pstr.0000112

Copyright: © 2024 Bączyk et al. This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Author summary

Sustainable infrastructural technology is crucial for addressing climate change and adaptation. However, recent geopolitical tensions show that technological development becomes increasingly intertwined with international relations as these tensions revolve around strategic technology, technological sovereignty, and market access. We investigate how international alliances, geographic proximity, and adoption by countries with similar political institutions influence the adoption of new technologies by countries. We look at the diffusion of six key infrastructure technologies among 161 countries during the past six decades: nuclear power, solar power, wind power, marine power, high-speed rail, and telecommunication satellites. Our analysis shows that international relations play a role in technology diffusion because cross-country technology adoption occurred between allied and neighboring countries rather than as an effect of politically similar countries imitating each other. The findings imply that promoting innovation and technology through diplomatic channels can support a country's strategic interest

Data Availability Statement: All data necessary to replicate the findings are publicly available under the following link: https://osf.io/7fvqg/.

Funding: KF and IW benefitted from the INTRANSIT project funded by the Norwegian Research Council, grant number 295021, https://www.forskningsradet.no/en/. The funder did not play any role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors have declared that no competing interests exist.

and facilitate the commercialization of technologies necessary for the transition to a more sustainable future.

Introduction

Technology plays a critical role in climate change mitigation and adaptation because it can help reduce greenhouse gas emissions and coping with the impacts of climate change [1,2]. For instance, renewable energy and low-carbon transportation technologies can decrease the dependence on fossil fuels, while better communication services are fundamental to coordinating response action in case of natural disasters. The diffusion of sustainable infrastructural technologies is thus an important constituent of the transition towards a more sustainable future.

However, technological development has become increasingly entrenched in international relations. After the fall of the Berlin Wall and the subsequent wave of democratization and liberalization, many believed the Cold War between post-war capitalist and communist blocs ended. Concerns about international security eroded and another cold war became unthinkable to many people [3,4]. Yet, the "end of history" did not last long. The international tensions intensified with the resurgence of Russia, and ever more so, with the rapid economic and technological development of China during the last two decades. In particular, Russia's autocratic rule and China's increased diplomatic efforts in Asia and Africa raised tensions with Western states [5]. The trade war between the United States and China, and intensified cooperation between Russia and China following Western sanctions are clear manifestations of these new developments [6], also referred to as the unfolding of a 'New Cold War' [7]. The Chinese threat to the supremacy of American digital technology, for example, prompted the United States to pressure European governments not to procure Chinese 5G technology [8].

Despite some similarities to the post-war conflict, the current tensions revolve less around ideology and more around strategic technology, technological sovereignty and market access [9–12]. Considering these geopolitical developments, countries are being forced to re-think their critical mineral supply, technology partnerships and political alliances. Thus, the role of international relations in cross-country technology diffusion needs to be examined.

Against this background, scholars have called for more integrated studies, combining economic, geographic and political perspectives in the analysis of technology adoption and sustainability transitions [9,13–15]. To fill this gap, we statistically analyze the role of international alliances as a spillover channel affecting technology adoption at national levels from the 1950s onwards. We look at the worldwide diffusion of six key infrastructural technologies during the past six decades: nuclear power, solar power, wind power, marine power; high-speed rail, and telecommunication satellites. We focus on infrastructural technologies as these usually require involvement of national governments. We expect international alliances to affect global technological diffusion, as adopting such technologies involves a complex procurement process based on sensitive information and a risky construction process prone to unforeseen problems and extensive delays. Hence, given this strong involvement of national governments in technology adoption [16], states may preferentially procure new infrastructural technologies from political allies rather than from any other states.

In this respect, we assume that 'innovation diplomacy'–understood as political support for innovation and diffusion across states through diplomatic means [17,18]–helps national governments in the complex technology adoption process. Particularly, we hypothesize that with each ally adopting a new technology, a state is more likely to adopt that technology as well.

Acknowledging that international relations go beyond formal political alliances, we further investigate the impact of 'institutional proximity' and 'geographical proximity' on technology diffusion. In general, one can expect that political, cultural and scientific exchange is most intense between states with similar political systems or between neighboring states. We thus also hypothesize that a state is more likely to adopt new technology, if institutionally similar or geographically close states already adopted the same technology in the past.

With our focus on political alliances as sources of spillovers in international technology diffusion, our study complements economic studies on technology diffusion emphasizing education and spillovers from trade [19–23]. And, compared to the recent study on technology diffusion determinants of one specific technology (nuclear power) by states in 79 countries [24], our work widens the scope of analysis: we examine the adoption of six technologies by states in 161 countries. This allows us to further scrutinize their findings for multiple technologies as well as to analyze possible differences in adoption patterns across technologies.

The rest of the paper is organized as follows: section 2 introduces a theoretical framework rooted in the theories of diffusion of innovation and international relations. Section 3 provides background information about the six selected technologies and explains the methodology. Section 4 discusses the results of the adoption analysis. The final section provides conclusions and issues for further discussion.

Theoretical framework

Technology diffusion is the process of proliferation of innovation in time within a social system from a source to an adopter, typically through channels of influence [23]. While most attention in technology diffusion research has been devoted to the adoption of innovation by individuals [25–27] or firms, we examine technology diffusion at the level of states by investigating the relationships between actors of the international system. In particular, regarding complex infrastructural technologies, the adoption of new technology involves the acquisition of knowledge and technology by national government bodies or other organizations embedded in a country's public sector. A country's international relations can then be understood as part of the channels of influence that affect technology adoption by states.

Observing diffusion from the vantage point of influence between adopters and non-adopters allows seeing diffusion as a temporal process of 'social contagion'. Using this lens has three advantages. First, it enables zooming in on the process underlying the diffusion of technologies [28]. Second, gives deeper insights into the forces behind so-called adoption S-curves [29,30] representing cumulative technology adoption over time. Third, it extends the analysis from investigating only the characteristics of the adopting entity to investigating the relationships between them. The concept of contagion originated in biological sciences to understand the spread of disease through close contact between individuals. It was subsequently used by sociologists to study the technology diffusion, starting with the seminal studies on diffusion of hybrid seed corn [25] and new drugs [26], and more recently also used by sustainability scholars to understand peer effects in the adoption of sustainable technologies (e.g., [27]).

The concept of diffusion also applies to transnational interdependence of decision-making. Decisions made by one state influence domestic change in other states. An example of a diffusion phenomenon is the falling domino effect used to describe the spread of communist regimes [31]. The dynamic of the falling domino shares similarities with the process of social contagion. Communism would spread in different regions through contagious contact [32]. While a change of political regime is just one instance of a diffusion process, other politically consequential phenomena such as technology can also cross borders [33].

We adopt a Westphalian understanding of the international state system in which states are sovereign actors within a system and exercise effective control within their borders [34,35]. When using the term country, we refer to the geographical area over which a state exercises its authority. We assume that states are monolithic actors and that interactions between states constitute the structure of the international state system [36,37]. Moreover, we further assume states enter alliances to coordinate their policies [38]. Apart from security and defense advantages, alliances might stem from pragmatic policy decisions, offering benefits such as trade, knowledge or access to technologies that they cannot produce domestically [38].

In the context of international relations, four mechanisms of diffusion have been distinguished: coercion, competition, learning, and emulation [39]. From the perspective of technology adoption, the most relevant mechanisms seem to be coercion, learning and emulation. In coercion, diffusion occurs through the pressure of other states, for example, to align a state's military technology to that of a leading ally. Learning means that experiences in other countries inform domestic decisions. Emulation means diffusion through mimicry, often through the copying of behavior of states perceived as leaders or more advanced [40].

The diffusion mechanisms of coercion and learning are supported by diplomatic interactions between states. In this context, Carayannis and Campbell [41] coined the term 'open innovation diplomacy', defined as: "the concept and practice of bridging distance and other divides (cultural, socioeconomic, technological, etc.) with focused and properly targeted initiatives to connect ideas and solutions with markets and investors ready to appreciate them and nurture them to their full potential." This understanding of innovation diplomacy as 'open' emphasizes the exchange of knowledge and technologies for seizing on economic opportunities stemming from technology diffusion.

Leijten [17] later argued that "the importance of national economic interests in the field is growing and puts issues like trade in high tech products, IP [intellectual property] ownership and protection, and standardization on the foreign policy agenda". In this light, Leijten [17] speaks of innovation diplomacy as "the use of the full spectrum of tools of the state to achieve its (national) innovation interest in the global geopolitical arena. It involves the use of diplomacy to facilitate innovation and the use of innovation to improve the relations between countries." Following this understanding, innovation diplomacy combines the field of international relations (with its orientation on political connections between states) and innovation policy (with its orientation on economic opportunities and learning). Hence, innovation diplomacy is not only directed at capturing the opportunities for economic development by adopting the latest technologies, but also at securing one's national interest, for example, by trading strategic technology only with trusted allies. Especially in turbulent times marked by financial, political or health crises, states attempt to secure a degree of technological sovereignty by generating technological knowledge domestically or using technological capabilities developed elsewhere by activating international partnerships [42].

Turning to the adoption decision of complex infrastructural technologies by states, it is important to first emphasize our definition of technology adoption in this context. We understand adoption as the use of a technology that is new to the country, and the time of adoption as the year in which the new technology is put to use. Understood in this manner, adoption can thus refer to the procurement of a technology from a country abroad or to the development of a technology by national organizations, or a combination of the two, with a foreign provider sourcing local content. That is, our definition refers solely to technology adoption, irrespective of where the technology is developed and produced [24].

Given that political allies have more established channels of communication as well as more aligned interests, both politically and economically, one can expect that states are primarily influenced by the adoption decisions by their allies. For a single state facing the decision to adopt a new technology or not, the chance of a state adopting a new technology will then depend on the number of allies already having adopted the technology, also called the 'geopolitical proximity' spillover effect on technological adoption [24]. This effect may result from multiple mechanisms. First, the more allies have already adopted a technology, the more information and experiences a state can collect from diverse allies. This improves the understanding of a technology, thus lowering investment uncertainties and improving a state's information position in contractual negotiations. Second, given the cumulative nature of technology development, the more allies have already adopted a technology, the more a state can profit from follow-up innovations provided by allies in the future. Finally, the adoption of technologies already in use by allies facilitates the use of the technology through shared international standards, certification systems, research projects and training programs. Our first hypothesis thus holds:

H1: *The more allies of a state adopt a technology*, *the more likely this state will also adopt this technology*.

The theory of diffusion of innovation further posits that adoption is more likely to occur if similar actors have already adopted the technology before [43]. This mechanism can play a role in emulation, as actors tend to observe and imitate actors that are most similar *viz*. 'proximate' to them on some relevant dimension. Regarding technology adoption by states, then, it would follow that states tend to adopt a particular technology if many proximate states have already adopted it in the past. As we deal with decisions about complex technologies involving national governments, one could argue that states with similar political institutions—also referred to as states with "institutional proximity" [44]–are likely to influence each other more than states with dissimilar political systems, also referred to as states that are institutionally distant. States with similar political systems will generally have more exchange of knowledge through various formal and informal channels as well as adopt similar technological standards and certification systems. Thus, the more two states are institutionally proximate, the more likely knowledge and technology will diffuse among them [44]. Hence, our second hypothesis becomes:

H_2: *The more states that are institutionally proximate to a state adopt a technology*, *the more likely this state will also adopt this technology*.

Along similar lines, one can argue that neighboring states, sharing borders, will generally have more exchange of knowledge and goods through various channels, their specific neighborhood policies as well as more similar technological standards and certification systems. Thus, for two geographically proximate states, it is more likely that knowledge and technology will diffuse among them [45]. Hence, our third and final hypothesis becomes:

H_3: *The more neighboring states of a state adopt a technology*, *the more likely this state will also adopt this technology*.

Data and methods

This study focuses on technology adoption at the country level and uses an extensive adoption margin. Our unit of analysis is, therefore, a country, and our dependent variable is the first adoption of a technology in that country at a particular time [24]. Over the period 1954–2012, we observe technology adoption of six key infrastructure technologies: nuclear power, solar power, wind power, marine power, high-speed rail, and telecommunication satellites. Due to the global scope of this study, we do not distinguish between different technological variants or standards of each technology, so as to encompass them in one analytical construct.

Our analytical framework is built around the international relations of states and the role of alliances in adopting certain technologies. Only sovereign states, capable of establishing and maintaining foreign relations, were considered for our study, meaning that dependent territories are omitted. In addition, in the period of observation, some states merged (e.g., Eastern and Western Germany into Germany) or split (e.g., Czechoslovakia into Czech Republic and Slovakia). These states were treated as separate entities of the international system in the case of discontinuity. For example, USSR disintegrated in 1991 into fifteen independent republics and Russia being considered a successor state was treated as a new entity. All states were examined meticulously across all data sources in terms of the beginning and the end of "statehood" to assure that the corresponding data points were assigned to the correct state before inserting them into our database.

Our analysis starts in 1954 with the first adoption of any of the six technologies and ends in 2012, after which data on political alliances was not available. The data was sourced from the Polity V dataset [46], see also S1 Table. Between 1954 and 2012, we have complete data for 161 countries; 45 countries were excluded from the sample because of a lack of data on the dependent variables. Finally, for the analysis of marine power technology, landlocked countries were excluded from the analysis because adoption of the technology is impossible. S1 Table contains the complete list of the countries with their official names, existence period, and comments on the exclusion from the study.

Dependent variables

In this study, we analyze six technologies. For each infrastructure technology, the dependent variable is a binary variable measuring technology adoption $(ADOPTION_t)$ of the technology in question by a country in a certain year t. The time of adoption corresponds to the year that a country adopts that technology. Thus, we constructed six different dependent variables of technology adoption.

We define *nuclear power* as electricity generation through nuclear fission in a nuclear reactor, which was first adopted in 1954 in the USSR [47]. Data on the year of adoption of nuclear power plants by states is sourced from the International Atomic Energy Agency (IAEA) [48], which provides a dataset on all power reactors in the IAEA member states. A country was considered an adopter once its first power plant became operational, with the adoption year set at the year of the grid connection (excluding nuclear power plants built for research purposes).

Regarding *solar power*, we looked at the two most common solar power technologies being photovoltaic panels (PV) starting in the United States in 1983 and concentrating solar-thermal power (CSP) starting a year later in the United States as well [49,50]. In PV technology, electricity is generated by solar cells converting the energy of light to electricity thanks to the photovoltaic effect. In CSP power plants, electricity is generated using turbines powered by steam produced with sunlight heat. We took solar power data from the Energy Information Administration (EIA) datasets on electricity generation [51]. A country is considered to become an adopter of solar power once electricity is generated by a utility-PV-park or a CSP-power-plant.

Wind power plants convert the kinetic energy of wind into electricity. Wind farms are groups of turbines either on land or offshore locations. The first modern wind farm was connected to the grid in Denmark in 1978 [52]. We took wind power data from the EIA datasets on electricity generation [51]. We considered a country an adopter of wind power once it started generating electricity from onshore or offshore wind farms.

We defined *marine power* as electricity generation from the energy harnessed from tides and waves [53]. The first tidal power plant was introduced in France in 1966, and the first wave power plant became operational in Portugal in 2008 [54]. Marine power data was also primarily sourced from the EIA dataset [51]. Contrary to solar and wind power, we established a criterion of at least 1MW of installed capacity to exclude demonstration projects connected to the grid that were below that capacity [55]. We supplemented the EIA data by identifying single installations through a review of academic papers and grey literature (all sources listed in Table 1). We considered a country an adopter of marine power once it started generating electricity from either tidal or wave power plants.

High-speed railways were pioneered by Japan with the introduction of the Shinkansen trai-nin 1964 [56]. We consider high-speed trains to be passenger train services operating at speeds crossing 250 km/h. What sets high-speed trains apart from conventional passenger trains are the dedicated infrastructure, locomotives with an in-cabin signaling system and system voltage of at least 25'000 V [57]. The adoption data is primarily based on the sources provided by the Union Internationale des Chemins de Fer (UIC) [58], complemented by a review of scientific literature (see Table 1). States were considered adopters in the year that high-speed trains started operating commercially in their country.

Finally, we investigate *telecommunication satellites*, with the first adoption in 1957—the launch of Sputnik 1 by the USSR [59]. In our study, satellite technologies refer to artificial satellites placed in the Earth's orbit. We consider telecommunication satellite technology relevant for sustainability transition because they enable connecting remote locations without extensive ground infrastructure, providing a vast range of communication services spanning from telephone calls over internet data to television broadcasting. For instance, they can also be used during natural disasters and emergencies when land systems are out of service, especially as natural disasters are expected to occur more frequently and have higher severity due to climate change. The primary data source was the Register of the Objects Launched into

Table 1. Variables and data.

Variable	Description and codes	Data sources	N countries
ADOPTION	1: country has adopted the technology 0: country has not adopted the technology	Nuclear power: [48]	205
		Solar power: [51]	195
		Wind power: [51]	195
		Marine power: [51,55,77–90]	195
		High-speed rail: [58,91–108]	205
		Telecommunication satellites: [60,109–111]	205
ALLIED	Count of state's allies that have adopted the technology	Derived from the dataset of formal alliances between countries: [61]	167
SIMILAR	Count of institutionally similar countries that have adopted the technology	Derived from the dataset of political regimes 'Polity V': [46]	178
NEIGHBORING	Count of neighboring countries that have adopted the technology	Derived from the dataset of sea and land borders between countries: [66]	205
REGIME	Polity score, ranging from -10 for full autocracy to 10 for full democracy	Dataset on political regimes 'Polity V': [46]	178
STABILITY	Number of years since the most recent regime change	Derived from the dataset on political regimes 'Polity V': [46]	178
GDP	Log transformed Gross Domestic Product of a country	Dataset on GDP: [112]	152
SURFACE	Country's surface in thousands of square kilometers	Dataset on country surface area: [72]	198
TRADE	Sum of exports and imports expressed as share of country's GDP	Dataset on trade openness: [112]	194
PATENTS	Log transformed number of patents filed by inventors from a country	Derived from the patent application dataset: [76]	181

https://doi.org/10.1371/journal.pstr.0000112.t001

Outer Space maintained by the United Nations [60]. States become adopters when they have at least one active satellite in orbit. We excluded satellites used for research or demonstration purposes as well as amateur satellites and lost missions (either due to launch failure or in-orbit failure) [24].

Independent variables

Adoption by allies. To test *H1*, we constructed a variable measuring the number of a state's military allies that already adopted a technology at each point in time and labeled it ALLIED. Military alliances serve here as a proxy for reconstructing the international system. We use alliance data from the Correlates of War (COW) project [61] because, to our best knowledge, it is the most comprehensive readily available dataset. The allies have been identified using the 'Formal Alliances v4.1' dataset on formal alliances between 1816 and 2012 which includes defense, entente, neutrality, and non-aggression pacts. We consider states allies only when they have signed either a defense or an entente treaty. While entente pacts are less formal than defense pacts, previous research shows that entente pacts also indicate strong bonds between states. In this respect, such pacts have been identified as more serious commitment than for instance non-aggression or neutrality pacts [62,63]. Thus, these two types of pacts were considered irrelevant because the signatories merely pledged to refrain from using military force. Furthermore, it has been noted that frequently such treaties were signed off by states after a settlement of a military dispute. Lastly, a five-year limit of minimal alliance duration was set to exclude temporary and less institutionalized commitments.

Institutional proximity. To test hypothesis *H2*, we constructed an institutional-proximity variable based on the similarity of political systems between states, labelled SIMILAR. We use the Polity V dataset [46], which contains longitudinal data on political regime characteristics and transitions between 1800 and 2018. For a measure of institutional proximity, we used the 'Polity' variable indicating the extent to which a national political system can be characterized as democracy versus autocracy, with–10 being full autocracy and +10 being full democracy. These scores are based on three institutional dimensions of the political systems: executive recruitment, independence of executive authority, and political competition and opposition [64]. We used country scores to construct a variable that measures the institutional proximity of a focal country to all prior adopter countries, by counting the number of prior adopters with a 'Polity' score 1 point higher or lower than the score of the focal country. We also do a robustness check by measuring similarity on a wider scale of [-2,+2].

Geographical proximity. To test *H3*, we constructed a geographical proximity variable measuring the number of neighboring adopter states [65]. At each moment in time, for a focal country, we count the number of neighboring states that already have adopted a technology. States were considered neighbors when they had either a land or a water border. For the water borders, we consider a shoreline distance between states of less than 24 miles [66]. The distance of 24 miles was selected because it reflects the overlap of territorial waters limits of 12 miles [67].

Control variables. To guard against potential confounders, we introduced six control variables: political regime, political stability, real GDP, country's surface area, trade openness and patents.

The first control variable is the political regime of the focal country. We control for the effects of the political regime of the focal country because previous studies found interactions between technology adoption and the type of political regime [21,24,68]. In particular, large-scale technologies such as nuclear energy may be easier to adopt for autocratic states because of the state's ability to ignore potential citizens' resistance against it, while small-scale technologies such as solar power may be preferred by more democratic states. Here, we use again the 'Polity' variable from the Polity V database, measured on a scale from –10 (full autocracy) to +10 (full democracy), [64].

As a second control variable, we include a measure of political stability. The temporal scope of setting up large infrastructural projects may exceed the temporal scope of rulers and or regime changes in many countries [24,69]. Frequent changes may impact the adoption intentions of decision-makers [70]. We use the 'Durable' variable from the Polity V database, which is operationalized as the number of years since the most recent regime change in the focal country. We label this control variable as STABILITY.

We also control for some socio-economic variables that can be expected to affect technology adoption. We use real GDP expressed in constant USD (log-transformed) taken from the World Development Indicators dataset maintained by the World Bank [71], as the adoption of large infrastructural technologies requires substantial investment [21].

We also use a country's SURFACE AREA, taken from the Food and Agriculture Organization of the United Nations (FAO) [72], since the country's size is an important adoption determinant in the case of infrastructural technologies. For instance, some of the technologies (such as solar parks, [73]) require a significant amount of land [69] or adoption is sensible only for large countries (i.e., high-speed rail or telecommunication satellites) because of the great distances between major population centers.

We further consider countries' trade openness, as this can positively affect technology adoption, especially in the case of trade with more technologically advanced partners [20,74]. We measure TRADE OPENNESS as the sum of a country's imports and exports expressed as the percentage of its GDP [71]. Trade data was only available from 1960 onwards (which only affects the analysis of nuclear power, whose first adoption was before 1960).

We finally include a control variable indicating the domestic knowledge base, as knowledge helps to adopt complex technologies [75]. For this, we constructed the variable PATENTS (log-transformed), for which we took the total number of utility patents filed by a country at the United States Patent and Trademark Office [76]. We specifically chose the number of filed patents as opposed to the number of granted patents to grasp the extent of the country's knowledge-generation capabilities.

Table 1 provides the full overview of our variables, measurements, data sources and coverage in terms of the number of countries.

Fig 1 summarizes the conceptual framework and provides a snapshot of the technologies included in the study.

Time-to-event analysis

To test the hypotheses, we used time-to-event analysis and specifically built an extended Cox model [113]. This model is used to study the impact of time-variant and time-invariant covariates on the risk of an event occurring, in our case on the adoption of an infrastructural innovation taking place by a state of a specific country in a specific year. An extended Cox model is specifically suitable for our study because it explicitly accounts for the right-censored nature of our adoption data, namely states that did not adopt a technology in the studied time frame but might decide to do so at a later stage. Furthermore, we used an extended Cox model, because including time-varying variables in our model would violate the proportional hazard assumption of a regular Cox model. All our independent and control variables are time-varying.

To estimate how different covariates associate with the risk of adoption, extended Cox models use exponential hazard functions that represent the risk that if at time t a country has not yet adopted a certain technology, this country will adopt this technology at some instance

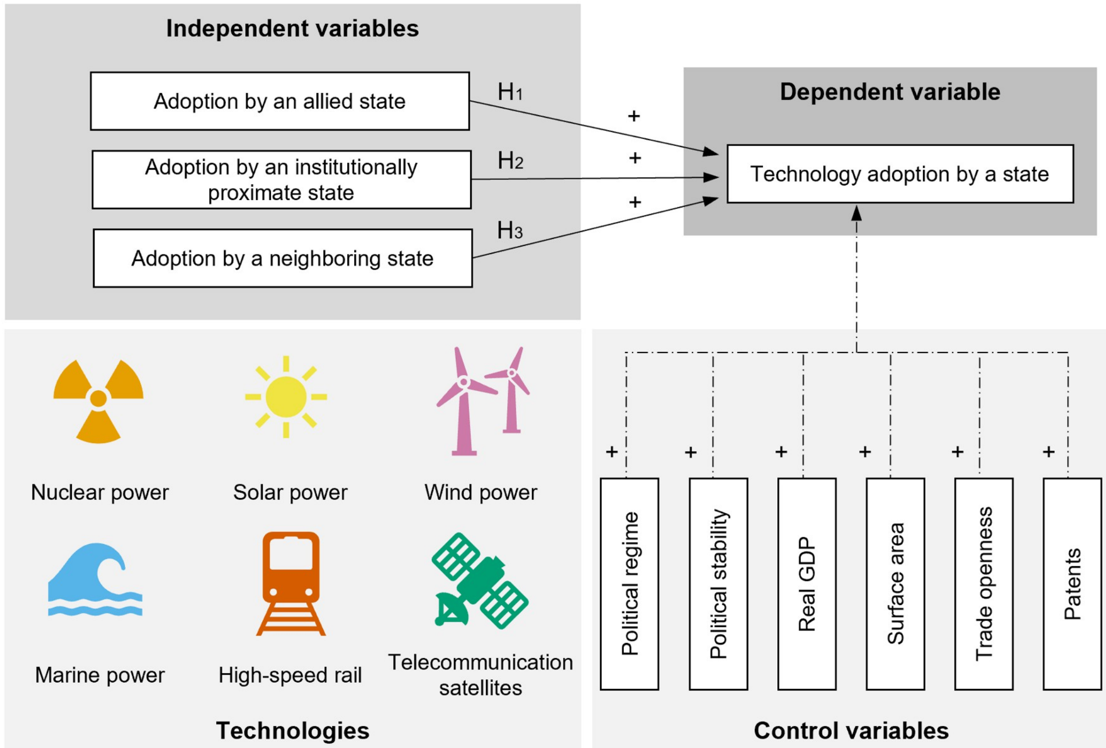

Fig 1. Overview of the variables and technologies.

https://doi.org/10.1371/journal.pstr.0000112.g001

later on. As a result, we format the data in such a way that each country receives a line for each time interval, which allows time-dependent variables to change for the same country over time [113]. The model uses the following equation to measure the influence of the different covariates:

$$h(t, X(t)) = h_0(t)\exp\left[\sum_{i=1}^{p^1} \beta_i X_i + \sum_{j=1}^{p^2} \delta_j X_j(t)\right]$$

where $h_0(t)$ is the baseline hazard function, X_i denotes the ith time-independent variables and $X_{(j)}(t)$ denotes the jth time-dependent variables and all predictors at time t are denoted by $\boldsymbol{X}(t)$ [113]. The baseline hazard function would estimate the risk of adoption for observations with 0 on all time-dependent and time-independent covariates and as such is only dependent on time. Time in our analysis is measured in years. We used the package *survival* in R to estimate our models.

Results

Descriptive statistics and adoption curves

Table 2 provides the descriptive statistics for the dependent variable, the three main independent variables associated with the three hypotheses, and the six control variables. The dependent and independent variables are presented separately because they differ per technology. For the sake of exposition, the descriptive statistics of the control variables are not presented

Table 2. Descriptive statistics.

Variable	Technology	N	Mean	SD	Min	Max
Adoption	Nuclear power	6534	0.01		0.00	1.00
	Solar power	3347	0.04		0.00	1.00
	Wind power	3943	0.02		0.00	1.00
	Marine power	5166	0.002		0.00	1.00
	High-speed rail	6583	0.002		0.00	1.00
	Telecommunication satellites	5753	0.01		0.00	1.00
Allied	Nuclear power	6534	1.41	2.66	0.00	18.00
	Solar power	3376	2.19	4.34	0.00	28.00
	Wind power	3956	1.90	3.67	0.00	26.00
	Marine power	5239	0.41	0.91	0.00	7.00
	High-speed rail	6582	0.35	1.34	0.00	10.00
	Telecommunication satellites	5752	1.41	2.96	0.00	21.00
Similar	Nuclear power	6398	4.25	6.16	0.00	26.00
	Solar power	3274	5.68	9.24	0.00	58.00
	Wind power	3846	4.58	8.84	0.00	55.00
	Marine power	5094	0.77	1.16	0.00	7.00
	High-speed rail	6469	1.16	2.51	0.00	13.00
	Telecommunication satellites	5668	4.88	7.13	0.00	30.00
Neighboring	Nuclear power	6534	0.47	0.93	0.00	7.00
	Solar power	3377	0.52	1.06	0.00	13.00
	Wind power	3957	0.49	0.93	0.00	9.00
	Marine power	5240	0.11	0.34	0.00	3.00
	High-speed rail	6583	0.10	0.38	0.00	3.00
	Telecommunication satellites	5753	0.45	0.80	0.00	8.00
Regime		7635	0.54	7.45	-10.00	10.00
Stability		7712	21.65	28.35	0.00	203.00
GDP (log)		6252	33.72	3.25	25.13	43.88
Surface area		6881	9.56	24.32	0.01	224.12
Trade openness		5638	68.17	45.97	0.02	437.33
Patents (log)		6221	3.13	4.06	0.00	18.04

https://doi.org/10.1371/journal.pstr.0000112.t002

for each of the six technologies but in an aggregated manner by compiling the control variables from all technologies, countries and years in a single database.

Fig 2 shows the adoption curves of all six infrastructure technologies between 1954 and 2012. We see that the use of each technology has increased over time. Most technologies continue to diffuse, except for nuclear power, which seems to have reached its ceiling in the 1990s. This has been explained by a lack of countries with high growth in electricity demand and sufficient capacities to build their first nuclear power station [24]. Solar and wind power have the highest diffusion rates and closely follow the theoretical S-curve. The diffusion of marine power remained low until 2000s when a technological breakthrough of wave power plants occurred [54]. Similarly, the diffusion of high-speed rail remained low, with a relatively large adoption lag between countries. The low adoption rates of the two latter technologies may be attributed to dependence on suitable geographical conditions necessary for adoption. Lastly, in the case of telecommunication satellites, we observe a sharp increase in the number of adopter counties in 1980's which can be explained by international launches.

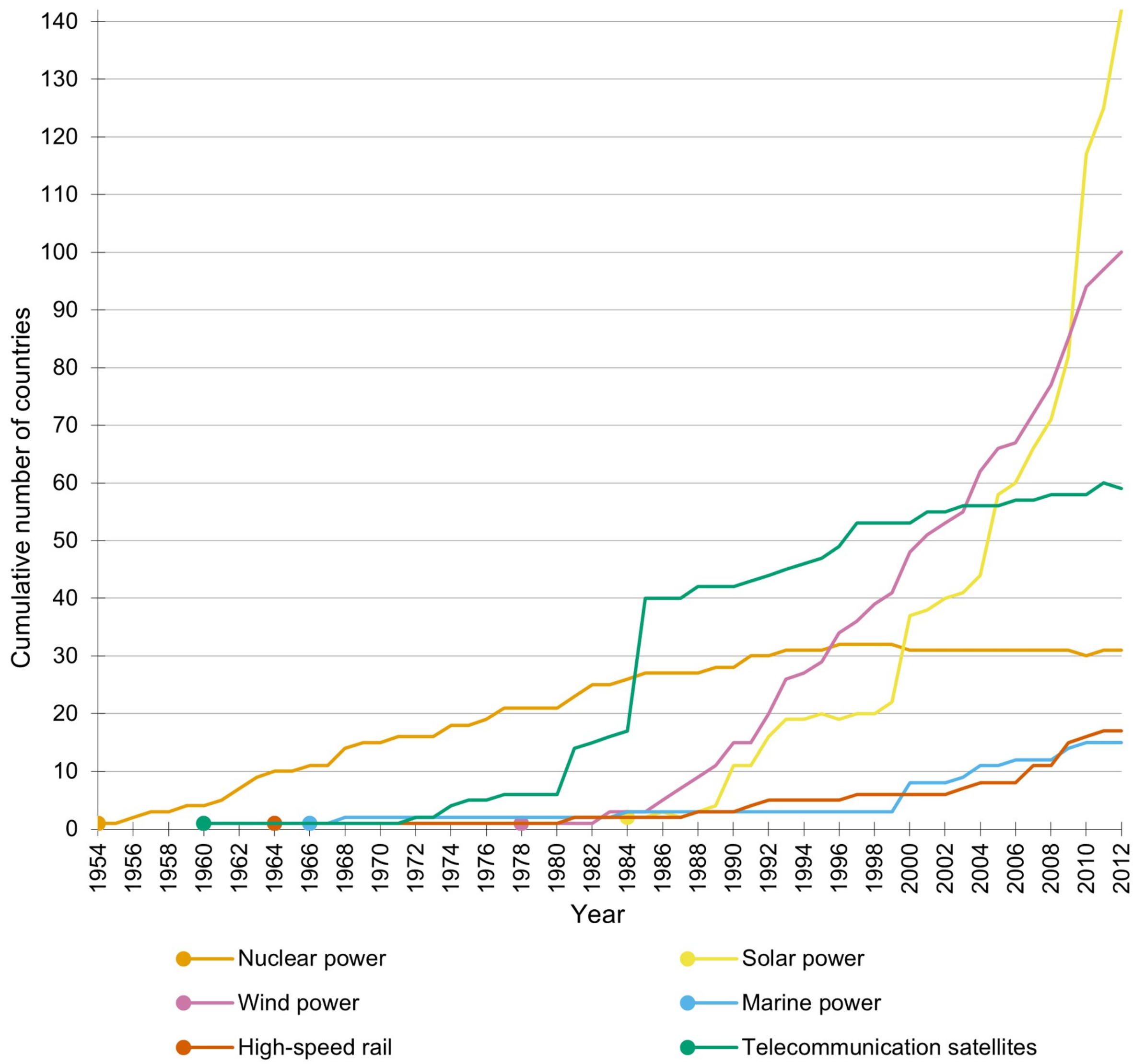

Fig 2. Adoption curve for the six technologies, 1954–2012.

https://doi.org/10.1371/journal.pstr.0000112.g002

Hypothesis testing

We built the model in a stepwise manner. S2 Table presents the full results of all six models, and for the sake of conciseness, Table 3 presents only *Model 5* and *Model 6* because we discuss the results of time-to-event analysis based on these two models. We focus on Model *5* and *Model 6* because they present the models including all three independent variables. The models differ in the number of spells and events, as *Model 6* includes fewer control variables and thus is less dependent on data availability for particular countries and years. Focusing on these results allows us to understand the effect of each key independent variable considering the impact of the other spillover channel. Note that (significant) coefficients larger than 1 indicate a positive effect and (significant) coefficients smaller than 1 indicate a negative effect.

Table 3. Extended Cox models (short version).

	Nuclear Power		Solar Power		Wind power		Marine power		High-speed rail		Telecommunication satellites	
	Model 5	Model 6	Model 5	Model 6	Model 5	Model 6	Model 5	Model 6	Model 5	Model 6	Model 5	Model 6
Allied	0.666***	0.876***	1.017***	1.005**	0.996	0.998	1.228***	1.364***	1.042**	1.141***	1.180***	1.214***
	-0.018	-0.01	-0.002	-0.002	-0.003	-0.002	-0.02	-0.02	-0.012	-0.011	-0.005	-0.003
Similar	0.901***	0.924***	0.965***	0.961***	1.029***	1.005***	0.598***	0.583***	0.681***	0.774***	0.951***	0.949***
	-0.008	-0.006	-0.002	-0.002	-0.001	-0.001	-0.037	-0.033	-0.018	-0.013	-0.004	-0.003
Neighboring	1.587***	1.949***	1.235***	1.121***	0.964***	1.258***	0.972	1.900***	3.411***	2.178***	1.050***	1.298***
	-0.022	-0.014	-0.009	-0.005	-0.011	-0.009	-0.065	-0.057	-0.038	-0.03	-0.014	-0.01
Regime	1.181***	1.112***	1.099***	1.109***	1.071***	1.123***	1.530***	1.478***	1.119***	1.206***	0.933***	1.056***
	-0.009	-0.004	-0.003	-0.003	-0.003	-0.003	-0.038	-0.029	-0.009	-0.008	-0.004	-0.002
Stability	0.966***	1.013***	1.007***	1.017***	1.005***	1.013***	0.986***	0.999	0.987***	1.007***	1.011***	1.023***
	-0.002	-0.001	-0.0004	-0.0003	-0.0004	-0.0004	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001
GDP (log)	1.652***		1.233***		1.453***		1.253***		3.734***		1.437***	
	-0.029		-0.01		-0.012		-0.04		-0.038		-0.016	
Surface area	1.012***		0.982***		1.005***		1.012***		0.970***		1.012***	
	-0.002		-0.001		-0.001		-0.001		-0.002		-0.002	
Trade openness	0.999		1.001		0.997***		0.996*		0.999		1.003***	
	-0.001		-0.0002		-0.0003		-0.002		-0.001		-0.0003	
Patents (log)	1.096***		1.049***		1		1.094***		0.846***		1.217***	
	-0.018		-0.007		-0.008		-0.022		-0.016		-0.011	
Number of spells	3,858	6,398	2,537	3,273	2,826	3,845	3,738	5,093	4,614	6,468	3,605	5,667
Events	13	36	104	119	79	89	10	10	13	13	47	62
Log-Likelihood	-6,844.62	-24,800.61	-67773.39	-81768.02	-48024.74	-56796.65	-7023.38	-7439.46	-9839.86	-13488.32	-28,833.37	-43,153.97
Maximum VIF	2.76	2.14	5.56	2.7	4.4	2.06	8.88	2.88	6.72	3.09	5.03	1.55

Standard errors in parentheses. Reported effects are hazard ratios (exponent of the coefficient).

*p<0.05;

**p<0.01;

***p<0.001.

https://doi.org/10.1371/journal.pstr.0000112.t003

Turning to hypothesis 1 regarding spillovers from allied states, we observe that for four out of six technologies the adoption by a state's allies indeed promotes adoption by that state. Hence, we find fair evidence confirming hypothesis 1. No effect, however, is found for wind power, while an unexpected negative effect is found for nuclear energy. This latter finding is rather surprising as nuclear energy technology is politically sensitive since the underlying technological knowledge overlaps with knowledge on nuclear weapons. Nevertheless, we do not find that adoption is spurred by adoption by allies. Possibly, given the geopolitical importance of nuclear know-how and capabilities, the adoption by states outside an alliance can be a reason to develop the know-how as well, which would explain the negative effect.

Hypothesis 2 suggests that states tend to imitate politically similar states. No evidence can be found for this effect, except for wind technology where a positive, albeit small, effect is found. Hence, we can clearly reject hypothesis 2. A further robustness check was carried out by measuring similarity not at the scale of [-1,+1] but a wider scale of [-2,+2], but the results obtained with this new scale also lead to a rejection of hypothesis 2.

Finally, hypothesis 3 suggests that states are affected by adoption decisions in neighboring states. We observe positive and significant effects for all technologies, except for wind and marine power. For these two technologies, we do not find such positive effects in Model 5 (with more variables but fewer observations) but we do find positive and significant effects in Model 6 (with fewer variables and more observations). This inconsistent finding may reflect that these two technologies depend the most on the local resource potential, namely harnessable wind and marine energy, which cannot be imported [114,115]. Overall, this shows that states may be very much influenced by neighboring states with whom governments tend to hold strong relations in many respects (e.g., political, cultural, economic, scientific, tourism). Nuclear power and high-speed trains show very high hazard ratios showing a very pronounced effect of adoption by neighboring states. For nuclear, this may relate to safety risks that cross borders which may provide an additional incentive to adopt if neighboring states have already adopted and, reversely, a disincentive to adopt as long as no neighboring state has adopted. The effect for high-speed trains can be explained by the fact that high-speed trains often connect cities in different countries, incentivizing states to collaborate on the construction of a joint high-speed line.

Control variables also present some interesting results. Regarding different political regimes, more democratic states tend to adopt new technologies faster than less democratic states. This result holds for all technologies except for telecommunication satellites. Stability also has a positive effect on adoption in most cases, but the effects are rather small compared to the effects of political regime. Economy size, as expressed in terms of GDP, has a significant and positive effect on adoption for all technologies, in line with an earlier nuclear power adoption study [24]. The surface area also has an effect on adoption with some interesting differences. While most technologies benefit from larger surface area as expected, a larger surface area seems to actually reduce adoption of solar and high-speed trains. These results may indicate that solar is especially attractive for states with little surface area available for larger-scale or more risky technologies. The results for high-speed rail may reflect that this transport technology cannot compete with airline travel over very long distances. Finally, patents affect adoption, as expected, but only for four out of the six technologies. For high-speed trains, unexpectedly, the effect is even negative.

In sum, the results are fairly consistent across technologies, for most technologies, we found evidence of spillover effects from allied states (hypothesis 1) and neighboring states (hypothesis 3) on technology adoption. No such evidence was found for states that are politically similar (hypothesis 2). These results suggest that international relations support technology diffusion at the state level, either by formal military alliances or by stronger relations among neighboring states due to economic and cultural exchange. The overall results, then, suggest that spillovers between states affecting adoption are channeled through international relations as well as neighboring states, rather than through simply mimicking politically similar states.

Discussion and concluding remarks

The purpose of this research was to scrutinize to what extent international relations affect technology adoption decisions by states. Based on a theoretical framework combining diffusion of innovation and international relations, we hypothesized that states whose allies have adopted a technology before are more likely to adopt this technology as well. We further hypothesized that states are also influenced by adoption by states with similar political systems (institutional proximity) and neighboring states (geographical proximity). For the six technologies we analyzed (nuclear power, solar power, wind power, marine power, high-speed rail, telecommunication satellites), we found evidence for spillovers between allied states as well as between neighboring states. No such evidence was found for institutionally similar states. These results confirm the important role that international relations may play in technology diffusion, as spillovers between states affecting adoption are channeled through international relations as these exist within alliances and among neighboring states, and not through an imitation process by states mimicking what politically similar states have done in the past.

Despite the high consistency of the Cox model coefficients between different technologies, we observed some variance across them, which could be explained by looking at technology-related factors such as complexity level, network effects, natural resource availability or criticality to national security. Notably, we also observe significantly high differences in diffusion rates between solar power and marine power for instance, as evidenced by the slopes of the diffusion curves in Fig 1. This suggests that innovation characteristics play a substantial role in the diffusion process, which also has been observed by Geroski [30] in his firm-level study of epidemic diffusion models. Further research should focus on enhancing our framework with both politically relevant technology characteristics and technology-specific factors to systematically assess the varying patterns across our sample. Ideally, including more technologies (i.e. wireless networks, new-energy vehicles, or military technologies, etc.) in our follow-up research would allow for validating our findings for technological sectors other than energy, transport and space.

Our study has some limitations. In particular, we have looked only at formal military alliances between states, while diplomatic ties go beyond such alliances. Given the lack of comprehensive data on other alliances, we have instead used the institutional and geographical proximity between states to proxy non-military diplomatic contacts. Second, because of the focus on states, the specific role of other international organizations was neglected. For instance, the states associated with the Arab League had a joint space program for telecommunication satellites. In this case, there was a nearly perfect overlap between the allied states and the adopters of technology. Most NATO member states have likewise cooperatively sent satellites to space, but the joint launches happened through European Space Agency (ESA) projects and not through cooperation within NATO structures. Third, we analyzed only the extensive adoption margin as data on the intensive adoption margins are lacking. This means that we could not account for the extent to which a given technology is used in a given country. Finally, despite triangulation and reliance on trustworthy sources, some of the data for solar and wind power in some countries could refer to non-utility scale installation. Consequently, the time of adoption of utility-scale adoption of solar and wind power is less reliable than for the other technologies investigated.

Our findings on the role of international relations on technology adoption speak to the recent literature on innovation diplomacy [17,18] and contribute to the literature on sustainability transitions by shedding light on the role of international relations in the diffusion of sustainable infrastructural technologies. Innovation diplomacy is part of a state's foreign policy, as exemplified by the role of innovation attachés in diplomacy offices [17]. It involves facilitating innovation and technology adoption and focuses on building national gains in science, technology, and innovation through diplomatic means. Similarly, Edler et al. [42] and Kivimaa et al. [116,117] point to the growing prominence of technology sovereignty in national innovation policies, in which states have to strategically deal with opportunities and constraints coming from international dependencies and interdependencies. In this context, Leijten [17] argues that innovation attachés can support the competitiveness of their nations by signaling collaboration opportunities and export markets. Thus, consistent with the theoretical framework in our study, such attachés can be seen as 'spillover' agents, who actively seek to influence technology adoption decisions, thus reinforcing both the economic and political interests of states [118]. In other words, diplomatic relationships offer means for the creation of contagion channels for international technology diffusion. This observation has two practical implications for policymakers. First, strengthening and expanding innovation diplomacy between states offer means of commercialization of sustainable technologies for producer countries as well as the security of supply of minerals and other critical inputs [119]. Based on this 'soft power' approach [120], a country like China has expanded its political and economic power [5]. Second, for countries that are not at the technological frontier, innovation diplomacy may support the attainment of their domestic sustainability goals by adopting (sustainable) technology from abroad while aligning these adoption decisions with strategic considerations of a political nature.

To conclude, our theoretical and methodological approach proved to be useful in studying the role of international relations in technology adoption by states. We showed that interactions between nation-states have a positive influence on technology diffusion. The differences in empirical results across technological sectors further suggest the 'contagiousness' of technologies may vary [68], while technologies may also be subject to different domestic policies [121]. More research is needed to follow up on the results and further the understanding of technology adoption determinants. Including technology-specific factors and policy changes offers a promise of more in-depth insights into this phenomenon.

Supporting information

S1 Table. State names, continuity, and exclusion notes.
(PDF)

S2 Table. Extended Cox models.
(PDF)

Author Contributions

Conceptualization: Michał Bączyk, Koen Frenken, Iris Wanzenböck.

Data curation: Michał Bączyk.

Formal analysis: Matthijs B. Punt.

Investigation: Michał Bączyk.

Methodology: Michał Bączyk, Koen Frenken, Iris Wanzenböck.

Validation: Iris Wanzenböck.

Writing – original draft: Michał Bączyk, Koen Frenken.

Writing – review & editing: Koen Frenken.

References

1. Blanco G, de Coninck HC, Agbemabiese L, Diagne EHM, Anadon LD, Lim YS, et al. Innovation, technology development and transfer. In: Shukla PR, Skea J, Al Khourdajie A, van Diemen R, McCollum D, Pathak M, et al, editors. IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, New York: Cambridge University Press; 2022. pp. 2674–814.
2. Sovacool BK. Hard and soft paths for climate change adaptation. Climate Policy. 2011; 11(4): 1177–83. https://doi.org/10.1080/14693062.2011.579315
3. From Trade War To Tech War To Cold War [Internet]. Hoover Institution Standford University []. https://www.hoover.org/research/trade-war-tech-war-cold-war
4. Fukuyama F. The end of history and the last man. London: Hamilton; 1992.
5. Jakobson L. China's diplomacy toward Africa: drivers and constraints. International Relations of the Asia-Pacific. 2009; 9(3): 403–33. https://doi.org/10.1093/irap/lcp008

6. Gould-Davies N. Russia, the West and Sanctions. Survival (London). 2020 Jan 2,; 62(1): 7–28. https://doi.org/10.1080/00396338.2020.1715060
7. Yao Y. The New Cold War: America's new approach to Sino-American relations. China Int Strategy Rev. 2021; 3(1): 20–33. https://doi.org/10.1007/s42533-021-00071-1
8. Jaisal EK. The US, China and Huawei Debate on 5G Telecom Technology: Global Apprehensions and the Indian Scenario. Open Political Science. 2020 Apr 22,; 3(1): 66–72. https://doi.org/10.1515/openps-2020-0006
9. Cherp A, Vinichenko V, Jewell J, Brutschin E, Sovacool B. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. Energy Research & Social Science. 2018; 37: 175–90. https://doi.org/10.1016/j.erss.2017.09.015
10. Van de Graaf T, Overland I, Scholten D, Westphal K. The new oil? The geopolitics and international governance of hydrogen. Energy Research & Social Science. 2020; 70: 101667. https://doi.org/10.1016/j.erss.2020.101667 PMID: 32835007
11. Kramarz T, Park S, Johnson C. Governing the dark side of renewable energy: A typology of global displacements. Energy Research & Social Science. 2021; 74: 101902. https://doi.org/10.1016/j.erss.2020.101902
12. UK Leader's 'Tech-NATO' Proposal Won't Tackle China's Technology Threats [Internet]. []. https://rusi.org/explore-our-research/publications/commentary/uk-leaders-tech-nato-proposal-wont-tackle-chinas-technology-threats
13. Falkner R. Global environmental politics and energy: Mapping the research agenda. Energy Research & Social Science. 2014; 1: 188–97. https://doi.org/10.1016/j.erss.2014.03.008
14. Binz C, Truffer B. Global Innovation Systems—A conceptual framework for innovation dynamics in transnational contexts. Research Policy. 2017; 46(7): 1284–98. https://doi.org/10.1016/j.respol.2017.05.012
15. Robertson Munro F, Cairney P. A systematic review of energy systems: The role of policymaking in sustainable transitions. Renewable and Sustainable Energy Reviews. 2020; 119: 109598. https://doi.org/10.1016/j.rser.2019.109598
16. Wejnert B. Integrating Models of Diffusion of Innovations: A Conceptual Framework. Annual review of sociology. 2002 Jan 1,; 28(1): 297–326. https://doi.org/10.1146/annurev.soc.28.110601.141051
17. Leijten J. Exploring the future of innovation diplomacy. Eur J Futures Res. 2017; 5(1): 1–13. https://doi.org/10.1007/s40309-017-0122-8
18. Griset P. Innovation Diplomacy: A New Concept for Ancient Practices? The Hague journal of diplomacy. 2020 Aug; 15(3): 383–97. https://doi.org/10.1163/1871191X-BJA10036
19. Caselli F, Coleman WJ. Cross-Country Technology Diffusion: The Case of Computers. American Economic Review. 2001 May 1,; 91(2): 328–35. https://doi.org/10.1257/aer.91.2.328
20. Hall BH, Khan B. Adoption of new technology. National bureau of economic research. 2003(No. w9730)
21. Coleman WJ. Comment on: "Cross-country technology adoption: making the theories face the facts". Journal of monetary economics. 2004; 51(1): 85–7. https://doi.org/10.1016/j.jmoneco.2003.05.001
22. Gong G, Keller W. Convergence and polarization in global income levels: a review of recent results on the role of international technology diffusion. Research Policy. 2003; 32(6): 1055–79. https://doi.org/10.1016/S0048-7333(02)00136-1
23. Pulkki-Brännström A, Stoneman P. On the patterns and determinants of the global diffusion of new technologies. Research Policy. 2013; 42(10): 1768–79. https://doi.org/10.1016/j.respol.2013.08.011
24. Brutschin E, Cherp A, Jewell J. Failing the formative phase: The global diffusion of nuclear power is limited by national markets. Energy Research & Social Science. 2021; 80: 102221. https://doi.org/10.1016/j.erss.2021.102221
25. Ryan B, Gross NC. The diffusion of hybrid seed corn in two Iowa communities. Rural Sociol. 1943; 8 (1): 15.
26. Coleman J, Katz E, Menzel H. The Diffusion of an Innovation Among Physicians. Sociometry. 1957; 20(4): 253–70. https://doi.org/10.2307/2785979
27. Curtius HC, Hille SL, Berger C, Hahnel UJJ, Wüstenhagen R. Shotgun or snowball approach? Accelerating the diffusion of rooftop solar photovoltaics through peer effects and social norms. Energy Policy. 2018; 118: 596–602. https://doi.org/10.1016/j.enpol.2018.04.005
28. Angst CM, Agarwal R, Sambamurthy V, Kelley K. Social Contagion and Information Technology Diffusion: The Adoption of Electronic Medical Records in U.S. Hospitals. Management Science. 2010 Aug; 56(8): 1219–41. https://doi.org/10.1287/mnsc.1100.1183

29. Diebolt C, Mishra T, Parhi M. Theoretical and Empirical Literature on Diffusion: A Move Towards a Broader Perspective. In: Dynamics of Distribution and Diffusion of New Technology. Cham: Springer International Publishing; 2016. pp. 15–44.
30. Geroski PA. Models of technology diffusion. Research policy. 2000; 29(4): 603–25. https://doi.org/10.1016/S0048-7333(99)00092-X
31. Gilardi F. Transnational diffusion: Norms, ideas, and policies. Handbook of international relations. 2012; 2: 453–77. https://doi.org/10.4135/9781446247587
32. Starr H. Democratic dominoes: Diffusion approaches to the spread of democracy in the international system. J Conflict Resolut. 1991; 35(2): 356–81.
33. Solingen E. Of Dominoes and Firewalls: The Domestic, Regional, and Global Politics of International Diffusion1. International studies quarterly. 2012 Dec 1,; 56(4): 631. https://doi.org/10.1111/isqu.12034
34. Krasner SD. Sovereignty and its discontents. In: Krasner SD, editor. Power, the state, and sovereignty: essays on international relations. London: Routledge; 2009.
35. Kaufman JP. Introduction to international relations. Lanham [u.a.]: Rowman & Littlefield; 2013.
36. Burchill S, Linklater A, Devetak R, Donnelly J, Nardin T, Paterson M, et al. Theories of international relations. 5th ed. Macmillan; 2013.
37. Donnelly J. Realism and international relations. Cambridge: Cambridge University Press; 2000.
38. Salmon T. The European Union: Just an alliance or a military alliance? Journal of strategic studies. 2006 Oct 1,; 29(5): 813–42. https://doi.org/10.1080/01402390600900911
39. Garrett G, Dobbin F, Simmons BA. Conclusion. In: Simmons BA, Dobbin F, Garrett G, editors. The Global Diffusion of Markets and Democracy. Cambridge: Cambridge University Press; 2008. pp. 344–60. https://doi.org/10.1017/CBO9780511755941.009
40. Marsh D, Sharman JC. Policy diffusion and policy transfer. Policy studies. 2009 Jun 1,; 30(3): 269–88. https://doi.org/10.1080/01442870902863851
41. Carayannis EG, Campbell DFJ. Open Innovation Diplomacy and a 21st Century Fractal Research, Education and Innovation (FREIE) Ecosystem: Building on the Quadruple and Quintuple Helix Innovation Concepts and the "Mode 3" Knowledge Production System. Journal of the Knowledge Economy. 2011; 2(3): 327. https://doi.org/10.1007/s13132-011-0058-3
42. Edler J, Blind K, Kroll H, Schubert T. Technology sovereignty as an emerging frame for innovation policy—Defining rationales, ends and means. Fraunhofer ISI, Karlsruhe; 2021. http://publica.fraunhofer.de/documents/N-638343.html
43. Kandel DB. Homophily, Selection, and Socialization in Adolescent Friendships. The American journal of sociology. 1978 Sep 1,; 84(2): 427–36. https://doi.org/10.1086/226792
44. Gertler MS. Tacit knowledge and the economic geography of context, or The undefinable tacitness of being (there). J Econ Geogr. 2003; 3(1): 75–99. https://doi.org/10.1093/jeg/3.1.75
45. Rossi-Hansberg E, Comin DA, Dmitriev MI. The Spatial Diffusion of Technology. Cambridge, Mass: National Bureau of Economic Research; 2012 Nov 1,http://www.nber.org/papers/w18534
46. Polity V dataset, version 2018 [Internet]. Marshall, Monty G. [cited 2020 December 20]. http://www.systemicpeace.org/polityproject.html
47. Rachkov VI, Kalyakin SG, Kukharchuk OF, Orlov YI, Sorokin AP. From the first nuclear power plant to fourth-generation nuclear power installations [on the 60th anniversary of the World's First nuclear power plant]. Thermal Engineering. 2014; 61(5): 327–36. https://doi.org/10.1134/S0040601514050073
48. Nuclear Power Reactors in the World [Internet]. International Atomic Energy Agency [cited 2021 January 31]. https://www.iaea.org/publications/14756/nuclear-power-reactors-in-the-world
49. Wolfe P. The Solar Generation: Childhood and Adolescence of Terrestrial Photovoltaics. 1st ed. Newark: John Wiley & Sons, Inc; 2018. https://doi.org/10.1002/9781119425618
50. Lovegrove K, Stein W. Introduction to concentrating solar power (CSP) technology. In: Lovegrove K, Stein W, editors. Concentrating solar power technology: principles, developments and applications. Elsevier; 2012. pp. 3–14. https://doi.org/10.1533/9780857096173.1.3
51. International Electricity Data [Internet]. U.S. Energy Information Administration [cited 2021 February 1]. https://www.eia.gov/international/data/world/world/electricity
52. Owens BN. Denmark Reinvents Wind Power. In: The Wind Power Story. 1st ed. Hoboken NJ, USA: Wiley; 2019. pp. 159–73. https://doi.org/10.1002/9781118794289.ch11
53. Clément A, McCullen P, Falcão A, Fiorentino A, Gardner F, Hammarlund K, et al. Wave energy in Europe: current status and perspectives. Renewable and Sustainable Energy Reviews. 2002; 6(5): 405–31. https://doi.org/10.1016/S1364-0321(02)00009-6

54. Frau JP. Tidal energy: promising projects: La Rance, a successful industrial-scale experiment. TEC. 1993 Sep; 8(3): 552–8. https://doi.org/10.1109/60.257073
55. Knowledge Base Marine Energy [Internet]. [cited 2021 February 17]. https://tethys.pnnl.gov/knowledge-base-marine-energy
56. Takatsu T. The history and future of high-speed railways in Japan. Japan Railway & Transport Review. 2007; 48: 6–21.
57. Campos J, de Rus G. Some stylized facts about high-speed rail: A review of HSR experiences around the world. Transport policy. 2009; 16(1): 19–28. https://doi.org/10.1016/j.tranpol.2009.02.008
58. High-Speed Database & Maps [Internet]. Union Internationale des Chemins de fer [cited 22.12.2020]. https://uic.org/passenger/highspeed/article/high-speed-database-maps
59. Gille L. Les satellites dans les réseaux de télécommunications: l'échec des constellations mobiles. Flux. 2001; 43(1):25–33
60. Online Index of Objects Launched into Outer Space [Internet]. United Nations Office for Outer Space Affairs [cited 2021January 25]. https://www.unoosa.org/oosa/osoindex/search-ng.jspx?lf_id=
61. The Correlates of War Project: Formal Alliances Dataset v4.1 [Internet]. [cited 2020 December 23]. https://correlatesofwar.org/data-sets
62. Gibler DM, Sarkees MR. Measuring Alliances: The Correlates of War Formal Interstate Alliance Dataset, 1816–2000. Journal of peace research. 2004 Mar 1,; 41(2): 211–22. https://doi.org/10.1177/0022343304041061
63. Krause V, Singer JD. Minor Powers, Alliances, and Armed Conflict: Some Preliminary Patterns. In: Small States and Alliances. Heidelberg: Physica-Verlag HD; 2001. pp. 15–23. https://doi.org/10.1007/978-3-662-13000-1_3
64. Marshall MG, Gurr TR. Dataset's User Manual: Polity 5:Political Regime Characteristics and Transitions, 1800–2018. Center for Systemic Peace; 2020.
65. Omobhude C, Chen S. The Roles and Measurements of Proximity in Sustained Technology Development: A Literature Review. Sustainability. 2019; 11(1) https://doi.org/10.3390/su11010224
66. The Correlates of War Project Direct Contiguity Data, Version 3.2 [Internet]. [cited 2020 December 23]. https://correlatesofwar.org/data-sets/direct-contiguity
67. Hensel PR. Documentation for COW Direct Contiguity Data—Version 3.20.; 2017.
68. Corrales J, Westhoff F. Information Technology Adoption and Political Regimes. International studies quarterly. 2006 Dec; 50(4): 911–33. https://doi.org/10.1111/j.1468-2478.2006.00431.x
69. Thurner PW, Mittermeier L, Küchenhoff H. How long does it take to build a nuclear power plant? A non-parametric event history approach with P-splines. Energy policy. 2014 Jul; 70: 163–71. https://doi.org/10.1016/j.enpol.2014.03.015
70. Aisen A, Veiga FJ. How does political instability affect economic growth? European Journal of Political Economy. 2013; 29: 151–67. https://doi.org/10.1016/j.ejpoleco.2012.11.001
71. World Development Indicators [Internet]. World Bank [cited 2020 December 23]. https://datacatalog.worldbank.org/dataset/world-development-indicators
72. Country surface area dataset [Internet]. Food and Agriculture Organization of the United Nations [cited 2021 April 19]. http://www.fao.org/faostat/en/#data/RL
73. Lumby B. Utility-scale solar photovoltaic power plants: a project developer's guide. 2015
74. Amidi S, Fagheh Majidi A. Geographic proximity, trade and economic growth: a spatial econometrics approach. Annals of GIS. 2020 Jan 2,; 26(1): 49–63. https://doi.org/10.1080/19475683.2020.1714727
75. Kim J, Lee S. Patent databases for innovation studies: A comparative analysis of USPTO, EPO, JPO and KIPO. Technological Forecasting and Social Change. 2015; 92: 332–45. https://doi.org/10.1016/j.techfore.2015.01.009
76. Number of Utility Patent Applications Filed in the United States, By Country of Origin, Calendar Years 1965 to Present [Internet]. U.S. Patent and Trademak Office [cited 2021 April 19]. https://www.uspto.gov/web/offices/ac/ido/oeip/taf/appl_yr.htm
77. Charlier RH, Finkl CW. Ocean energy. 1. Aufl. ed. Berlin [u.a.]: Springer; 2009.
78. Chowdhury MS, Rahman KS, Selvanathan V, Nuthammachot N, Suklueng M, Mostafaeipour A, et al. Current trends and prospects of tidal energy technology. Environ Dev Sustainability. 2020: 1–16. https://doi.org/10.1007/s10668-020-01013-4 PMID: 33041645
79. Falcão AFO, Sarmento AJNA, Gato LMC, Brito-Melo A. The Pico OWC wave power plant: Its lifetime from conception to closure 1986–2018. Applied ocean research. 2020 May; 98: 102104. https://doi.org/10.1016/j.apor.2020.102104

80. Fedorov MP, Shilin MB. Ecological safety of tidal-power projects. Power Technol Eng. 2010; 44(2): 117–21. https://doi.org/10.1007/s10749-010-0152-x

81. Greaves D, Iglesias G. Wave and tidal energy. John Wiley & Sons; 2018. https://doi.org/10.1002/9781119014492

82. International Renewable Energy Agency. Renewable Capacity Statisitics 2019. Abu Dhabi: International Renewable Energy Agency; 2019. https://www.irena.org/publications/2019/Mar/Renewable-Capacity-Statistics-2019

83. Jacobson MZ, Delucchi MA, Bauer ZAF, Goodman SC, Chapman WE, Cameron MA, et al. 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. Joule. 2017 Sep 6,; 1(1): 108–21. https://doi.org/10.1016/j.joule.2017.07.005

84. Kim G, Lee ME, Lee KS, Park J, Jeong WM, Kang SK, et al. An overview of ocean renewable energy resources in Korea. Renewable & sustainable energy reviews. 2012 May; 16(4): 2278–88. https://doi.org/10.1016/j.rser.2012.01.040

85. Leijon M, Boström C, Danielsson O, Gustafsson S, Haikonen K, Langhamer O, et al. Wave Energy from the North Sea: Experiences from the Lysekil Research Site. Surv Geophys. 2008; 29(3): 221–40. https://doi.org/10.1007/s10712-008-9047-x

86. Mikladal PA. Sustainable energy in the Faroe Islands–the role of hydropower. 2008

87. Narula K. Renewable Energy from Oceans. In: The Maritime Dimension of Sustainable Energy Security. Singapore: Springer Singapore; 2018. pp. 163–86.

88. Kofoed JP, Neumann F, Azevedo EdB, Le Crom I, Pecher A. Performance Assessment of the Pico OWC Power Plant Following the Equimar Methodology. ISOPE;2011.

89. Savidge G, Ainsworth D, Bearhop S, Christen N, Elsaesser B, Fortune F, et al. Strangford Lough and the SeaGen Tidal Turbine. In: Marine Renewable Energy Technology and Environmental Interactions. Dordrecht: Springer Netherlands; 2014. pp. 153–72.

90. Wang ZJ, Wang ZW. A review on tidal power utilization and operation optimization. IOP conference series. Earth and environmental science. 2019 Mar 1,;240(5): 52015.

91. Akiyama Y. High-speed rail worldwide—past and future. Japan Railway & Transport Review. 2014; 64 (64)

92. Amos P, Bullock D, Sondhi J. High-Speed Rail: The Fast Track to Economic Development? World Bank, Beijing; 2010 Jul. http://hdl.handle.net/10986/27812

93. Barrow K. Russia's Peregrine Falcon takes flight. 2009 Dec 1,; 49(12):34

94. Bouley J. Short history of "high-speed"railway in France before the TGV. Japan Railway & Transport Review. 1994; 3: 49–51.

95. Chou P, Lu C, Chang Y. Effects of service quality and customer satisfaction on customer loyalty in high-speed rail services in Taiwan. Transportmetrica (Abingdon, Oxfordshire, UK). 2014 Nov 26,; 10 (10): 917–45. https://doi.org/10.1080/23249935.2014.915247

96. Dilshod B, Nazirjon A, Davron R. Formalization of tasks of synthesis of intellectual control systems of technological processes of high-speed railway transport. Chemical Technology, Control and Management. 2018; 2018(3): 41–6.

97. Engelhardt J. Perspektywy rozwoju sieci kolei dużych prędkości w Unii Europejskiej do 2050 roku. Przegląd Komunikacyjny. 2019; 74

98. Gieras JF. Modern high-speed trains. Elektron. 1995; 12(1): 7–9.

99. Givoni M. Development and Impact of the Modern High-speed Train: A Review. Transport reviews. 2006 Sep 1,; 26(5): 593–611. https://doi.org/10.1080/01441640600589319

100. Hove K. The Oresund Line breaks the barrier. Rail Int. 2000

101. Hughes M. High Speed Trains-a Second Golden Age for Railways? JR East Technical Review. 2006 (8)

102. Massel A. Dostosowanie linii konwencjonalnych w wybranych zarządach kolejowych do prędkości jazdy równej lub większej od 200 km/h. Problemy Kolejnictwa—Railway Reports. 2018 Mar(178): 33–46. https://doi.org/10.36137/1783p

103. Melibaeva S. Development Impacts of high-speed rail: megalopolis formation and implications for Portugal's Lisbon-Porto High-Speed Rail Link [dissertation]. Massachusetts Institute of Technology; 2010 http://hdl.handle.net/1721.1/60807

104. Narvesen O. The Oslo Airport Express train. Japan Railway & Trransport review. 1999

105. Popov V, Chowdhury A. What Can Uzbekistan Tell Us about Industrial Policy that We Did Not Already Know? New York: United Nations; 2016 Feb 29

106. Stripple H, Uppenberg S. Life cycle assessment of railways and rail transports—Application in environmental product declarations (EPDs) for the Bothnia Line. IVL Svenska Miljöinstitutet; 2010. https://www.ivl.se/english/ivl/publications/publications/life-cycle-assessment-of-railways-and-rail-transports—application-in-environmental-product-declarations-epds-for-the-bothnia-line.html

107. Westwood JN. The High-Speed Railway. In: Soviet Railways to Russian Railways. Springer; 2002. pp. 152–65.

108. Zhou L, Shen Z. Progress in high-speed train technology around the world. Journal of Modern Transportation. 2011; 19(1): 1–6. https://doi.org/10.1007/BF03325733

109. Velká encyklopedie družic a kosmických sond [Internet]. Library of Czech Academy of Sciences [cited 2021 March 3]. https://www.lib.cas.cz/space.40/INDEX1.HTM

110. General Catalog of Artificial Space Objects, Release 1.1.10, [Internet]. McDowell, Jonathan C [cited 2021 February 12]. https://planet4589.org/space/gcat

111. Space Science Data Coordinated Archive [Internet]. National Aeronautics and Space Administration [cited 2021 March 25]. https://nssdc.gsfc.nasa.gov/nmc/SpacecraftQuery.jsp

112. Trade openness[Internet]. World Bank [cited 2021 January 21]. https://data.worldbank.org/indicator/NE.TRD.GNFS.ZS?end=2019&start=1960

113. Kleinbaum DG, Klein M, Kleinbaum DG, Klein M. Extension of the Cox proportional hazards model for time-dependent variables. In: Survival analysis: A self-learning text. Springer; 2012. pp. 241–88. https://doi.org/10.1007/978-1-4419-6646-9_6

114. Lu X, McElroy MB. Chapter 4—Global Potential for Wind-Generated Electricity. In: Wind Energy Engineering. Elsevier Inc; 2017. pp. 51–73.

115. Weiss CVC, Guanche R, Ondiviela B, Castellanos OF, Juanes J. Marine renewable energy potential: A global perspective for offshore wind and wave exploitation. Energy Conversion and Management. 2018; 177: 43–54. https://doi.org/10.1016/j.enconman.2018.09.059

116. Kivimaa P, Brisbois MC, Jayaram D, Hakala E, Siddi M. A socio-technical lens on security in sustainability transitions: Future expectations for positive and negative security. Futures. 2022; 141: 102971. https://doi.org/10.1016/j.futures.2022.102971

117. Kivimaa P. Transforming innovation policy in the context of global security. Environmental Innovation and Societal Transitions. 2022; 43: 55–61. https://doi.org/10.1016/j.eist.2022.03.005

118. Okano-Heijmans M. Japan's'green' economic diplomacy: environmental and energy technology and foreign relations. Pacific review. 2012 Jul 1,; 25(3): 339–64. https://doi.org/10.1080/09512748.2012.685090

119. International Energy Agency. The Role of Critical Minerals in Clean Energy Transitions. Paris: 2021. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

120. Yakushiji T. The Potential of Science and Technology Diplomacy. Asia-Pacific review. 2009 May 1,; 16 (1): 1–7. https://doi.org/10.1080/13439000902957640

121. Schaffer LM, Bernauer T. Explaining government choices for promoting renewable energy. Energy Policy. 2014; 68: 15–27. https://doi.org/10.1016/j.enpol.2013.12.064