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

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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.

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.
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:

H2: 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:

H3: 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 train in 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.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description and codes</th>
<th>Data sources</th>
<th>N countries</th>
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</thead>
<tbody>
<tr>
<td>ALLIED</td>
<td>Count of state’s allies that have adopted the technology</td>
<td>Derived from the dataset of formal alliances between countries: [61]</td>
<td>167</td>
</tr>
<tr>
<td>SIMILAR</td>
<td>Count of institutionally similar countries that have adopted the technology</td>
<td>Derived from the dataset of political regimes ‘Polity V’: [46]</td>
<td>178</td>
</tr>
<tr>
<td>NEIGHBORING</td>
<td>Count of neighboring countries that have adopted the technology</td>
<td>Derived from the dataset of sea and land borders between countries: [66]</td>
<td>205</td>
</tr>
<tr>
<td>REGIME</td>
<td>Polity score, ranging from –10 for full autocracy to 10 for full democracy</td>
<td>Dataset on political regimes ‘Polity V’: [46]</td>
<td>178</td>
</tr>
<tr>
<td>STABILITY</td>
<td>Number of years since the most recent regime change</td>
<td>Derived from the dataset on political regimes ‘Polity V’: [46]</td>
<td>178</td>
</tr>
<tr>
<td>GDP</td>
<td>Log transformed Gross Domestic Product of a country</td>
<td>Dataset on GDP: [112]</td>
<td>152</td>
</tr>
<tr>
<td>SURFACE</td>
<td>Country’s surface in thousands of square kilometers</td>
<td>Dataset on country surface area: [72]</td>
<td>198</td>
</tr>
<tr>
<td>TRADE</td>
<td>Sum of exports and imports expressed as share of country’s GDP</td>
<td>Dataset on trade openness: [112]</td>
<td>194</td>
</tr>
<tr>
<td>PATENTS</td>
<td>Log transformed number of patents filed by inventors from a country</td>
<td>Derived from the patent application dataset: [76]</td>
<td>181</td>
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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 $H_1$, 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 $H_2$, 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 $H_3$, 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...
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:

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

where \(h_0(t)\) is the baseline hazard function, \(X_i\) denotes the \(i\)th time-independent variables and \(X_{ij}(t)\) denotes the \(j\)th time-dependent variables and all predictors at time \(t\) are denoted by \(X(t)\) [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 \textit{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.
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.

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<td>Trade openness</td>
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<td>Patents (log)</td>
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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.
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)

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