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Resolving the patents paradox in the era of COVID-19 and climate change: Towards a patents taxonomy

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ABSTRACT

This paper revisits the patents debate and considers the role of intellectual property rights and their impact on society in the context of inventions designed to protect global common pool resources (CPRs) such as public health and the environment. A review of the theoretical and empirical literature suggests that there has never been a clear consensus among researchers on the benefits of the patent system and intellectual property rights. As Robinson notes, "The patent system introduces some of the greatest of the complexities in the capitalist rules of the game and leads to many anomalies." We explore these anomalies by specifying a taxonomy of patents for different classes of inventions, including inventions to protect CPRs. This includes vaccines and inventions that reduce externalities, such as, CFC gases and greenhouse gas emissions. In these instances, the effectiveness of innovations depends critically on rapid global diffusion. Our theoretical analysis utilises Ostrom's CPR dilemma to analyse the complexities surrounding innovation and CPRs.

We find that the effectiveness of innovations to protect CPRs depends on industrial characteristics and the wider regulatory environment. Empirical evidence is brought to bear on these conclusions via 2 case studies that each embodies a natural experiment; one on vaccines pre- and post-TRIPS and one on environmental technologies to reduce CFC gases and CO_2 emissions with and without an agreed UN Protocol. The insights gained are explored in our policy section. Our analysis suggests the need for a more nuanced approach to patent policy that is embedded in the wider context of innovation systems and takes account of the anomalies raised by CPRs. For CPR protecting innovations subject to positive network externalities, we advocate that policy should prioritise diffusion over private incentives for R&D and use alternative policies to patents to stimulate investment in R&D.

> "*This leads to what we may call the paradox of patents. A patent is a device to prevent the diffusion of new methods before the original investor has recovered profit adequate to induce the requisite investment. The justification of the patent system is that by slowing down the diffusion of technical progress it ensures that there will be more progress to diffuse. … Since it is rooted in a contradiction, there can be no such thing as an ideally beneficial patent system, and it is bound to produce negative results in particular instances, impeding progress unnecessarily, even if its general effect is favourable on balance.*"
>
> Robinson (1956, p. 87)

1. Introduction

The system of intellectual property rights introduced under the TRIPS Agreement is now over a quarter of a century old. While early patent laws can be traced back to the 15th Century, the consolidation of national laws under a single international system marked a milestone in the history of intellectual property rights (IPR) - a remarkable achievement not least because agreement on policy was reached without a consensus in the academic literature on the benefits of patents (Machlup and Penrose, 1950). This paper revisits the patents debate and considers

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the role of IPRs and their impact on society in the context of inventions designed to protect common pool resources (CPRs) such as public health and the environment. In particular, we seek to address the question of whether the patent system is fit for purpose to meet 21st Century challenges. Within that context, a central question is whether the one-size-fits-all approach to patents under TRIPS allows sufficient flexibility to avoid social costs (Kapp, 1963) and meet global challenges for all classes of invention from vacuum cleaners to vaccines.

While the recent history of patent law over the past 25 years is a fairly settled one from a legislative point of view, the longer run picture tells a different story with various countries adopting, abolishing and then readopting and revising patent laws. Some early patent laws, for example, the United States 1790 Patent Act, specified detailed assessment of each application[2] to determine whether inventions were 'useful and important', while other patent laws excluded certain products from patents, for example, food and medicines in England prior to 1949 and some other countries (Machlup, 1958, pp. 8/9) before the emergence of the current system where assessment is made primarily on the basis of originality.[3] This 'patent schizophrenia' reflects the lack of consensus in the academic literature on the costs and benefits of patents. Investing in R&D is a risky activity and the returns are uncertain. In the absence of policy interventions there is likely to be underinvestment for a variety of reasons. At the same time, most of the benefits to society come not from the R&D or the invention itself, but from its widespread diffusion. A central question at the core of the patents controversy is whether patents can generate sufficient private sector investment in R&D to outweigh the costs of preventing or slowing down diffusion for a considerable time period – normally 20 years. As Robinson (1956, p. 86) noted, "[t]he patent system introduces some of the greatest of the complexities in the capitalist rules of the game and leads to many anomalies." Today, COVID-19 and the climate crisis have accentuated those anomalies and put them under the spotlight of intense public scrutiny.

In this paper we revisit the patents debate in light of the current one-size-fits-all policy system and consider the case for a more granular approach that goes beyond assessment based on originality and infringement of IPRs. We argue that it is important to explore, rather than ignore anomalies, and to consider a variety of cases characterised by: (i) different industry structures/contexts; (ii) variation in the extent and nature of network externalities; and (iii) the wider regulatory environment within the context of regional, national and global innovation systems. Accordingly, we set out a taxonomy of patents/inventions that includes cases of patenting of technologies designed to preserve or enhance common pool resources (CPRs), as these are critical in the current era of COVID-19 and climate change.

CPRs are characterised by two key features: (i) they are non-excludable or virtually non-excludable, so that it is difficult to prevent individuals from benefiting from their use; and (ii) they are subtractable so that one person's use detracts from the total amount of the resource available for others. Examples of CPRs include common grazing land, fish stocks, the atmosphere and carbon sinks. The COVID-19 pandemic has underlined the fact that air free from viral infections is a CPR. The non-excludability and subtractability of CPRs make them subject to the tragedy of the commons and the related CPR dilemma (Ostrom, 1990; Ostrom et al., 1994), hallmarked by a conflict between individual (private) and collective (public) interests. Individual actors benefit from the use of CPRs but bear only a fraction of the cost of their depletion, resulting in their overuse and destruction. Ostrom et al. (1994) and Ostrom (1990; 2008) show that it may be possible to govern the commons by appropriate institutional arrangements, for example agreements to tie up fishing boats or limit carbon emissions, but they recognise that such arrangements are more difficult to attain in the case of the global commons. This is illustrated by cross country variations in governance measures such as mask wearing, testing, track and trace systems, social distancing and lock-down during the COVID-19 pandemic.

Another way of resolving CPR dilemmas is via innovation. Inventions, such as, vaccines and green technologies may protect CPRs but to be effective in preventing climate change and infectious diseases, they must be rapidly diffused. Building on Robinson's (1956) *paradox of patents*, consideration of the relationship between the efficacy of innovations and their speed of diffusion provides a means of determining when the effects of patents are likely to be more or less negative. It thus provides insight into how the *paradox of patents* may be resolved. To explore this idea, we set out a taxonomy of patents that systematically considers the factors influencing the ability of innovations to protect CPRs, including the relationship between the *efficacy* of inventions and the speed and extent of diffusion. A key question in this regard is to identify the conditions under which the *efficacy* of CPR-protecting innovations is affected by the speed and extent of diffusion, i.e. to determine when the use-value of CPR-protecting innovations is a function of the speed of diffusion.

The remainder of the paper is organised as follows. Section 2 revisits the patents controversy and provides a review of the literature setting out some of the key issues occasioned by COVID-19 and climate change. Section 3 provides a conceptual framework for our analysis setting out a taxonomy to inform the design of policies to promote innovation and diffusion. Within this taxonomy we focus on the complex case of inventions to protect CPRs, such as vaccines and low/zero-carbon technologies using the concept of the CPR dilemma. Section 4 presents our empirical analysis using case studies as natural experiments (Lee, 1989). Here we compare the development, diffusion and efficacy of vaccines for polio, which took place prior to TRIPS and without the use of patents, with the development of vaccines for COVID-19 post TRIPS. We also consider an intermediate case of HIV/AIDS drugs and the use of compulsory licensing. In relation to climate change, we consider the challenges posed by CFC gases and policies to eliminate their use under the UN Montréal Protocol, and recent policies to encourage the diffusion of low/zero emissions vehicles. These are contrasting cases, one governed by a universally ratified UN Protocol to eliminate CFC gases by setting a common standard supported by funding for technology transfer and patent costs, the other with a looser set of policies including the Nationally Determined Contributions of the Paris Agreement. Difference in difference analysis is used to shed light on the effect of Toyota's voluntary patent fee waiver. Section 5 discusses the policy implications of our taxonomy and empirical analysis for the system of IPR and the diffusion of innovations to protect CPRs.

2. Patents pre and post-TRIPS: a review of the literature

The contested origins of the contemporary patent system provide insight into the scale of the challenge now facing the use of innovations to protect CPRs. The origins of the contemporary patent system can be traced to a compromise between protectionist and free trade interests (Machlup, 1958). This resolution was not only controversial but also left unresolved questions over its ability to meet society's demand for technological progress and the extent of the social loss involved in "the temporary prevention of the use of the most efficient process by most if not all other producers" (Machlup and Penrose, 1950:24). The extent of

[2] Frederico (1936) noted that the time-consuming nature of the assessment process led Jefferson (the highest profile member of the 3-person Board) to argue for the removal of 'rigid examination' moving to a system of 'no examination' in the subsequent 1793 act, before examination with a lighter touch was 're-introduced' in the 1836 Act. Similarly, Biagioli (2019, pp.161-162) notes that under the 1790 Act determination of 'usefulness and importance' on a case-by-case basis, was time consuming and led to a back-log.

[3] Though even here patent law has been influenced by case law as legislators have had to navigate cases involving DNA, synthetic DNA and human genes, for example, Myriad Genetics' attempt to patent the breast cancer gene in 1994 went to the US supreme court, who ruled against Myriad Genetics (Pistor, 2019).

the social loss is already apparent in environmental CPRs where much of the technology for sustainable development already exists (Clugston, 2021); what is missing is an appropriate mechanism to support its rapid diffusion. In reviewing the many unresolved complexities of the current patent system with reference to the protection of CPRs, this section sets out the issues a taxonomy needs to address. This approach acknowledges the patent system as a less than ideal starting point but seeks to address what Machlup (1958: 80) viewed as improving the "basis for decision on 'a little more or a little less' of various ingredients of the patent system".

2.1. The contested evolution of the patent system pre and post TRIPS

While there has long been academic consensus on the centrality of invention to economic development and growth, the evolution of the patent system shows far less consensus on the role of patents in promoting innovation and diffusion. The main deficiency in the patent system was its attempt to achieve a purpose that cannot be achieved by parcelling up streams of creative thought into a series of distinct appropriable claims (Polanyi, 1944; Robinson, 1956; Dosi et al., 2006). Critics disputed the view that without the patent system there would be insufficient levels of inventions and that patents represented the most efficient form of promoting invention (Machlup and Penrose, 1950). For much of the 1800s the case for patents seemed lost in several European countries (Machlup, 1958). Evidence from exhibits at world fairs in 1851 and 1876 indicate high levels of quality inventions in countries such as Switzerland and Denmark with no patent laws and prizes for exhibits from the Netherlands where patents were abolished in 1869 (Moser, 2013; Schiff, 1971).

The superiority of the patent system rested on its ability to protect the difficult and relatively scarce activity of inventing, while placing codified knowledge in the public domain (Machlup, 1958; Polanyi, 1944). In this regard, patents came to offer a standard remedy for the market failure problem facing the developers of costly but promising technologies, since it offers a mechanism to appropriate some of the gains of later innovations (Arthur, 1989). Crucially this rests on the assumption that it is invention rather than innovation which the patent system is designed to protect. But because knowledge is for the most part a public good, addressing market failure by creating appropriability in this way also depends on ensuring artificial scarcity to amend for non-rivalry and non-excludability in use (Dosi et al., 2006).

In practice the conditions for appropriability are rarely perfect and vary substantially across sectors and countries (Levin et al., 1987; Torrisi et al., 2016). Tight appropriability tends to be the exception rather than the rule and such complementary assets as manufacturing and distribution capabilities are central to maintaining competitive advantage (Teece, 1986). This in turn has meant that many patents are either not used or are used as a strategic tool to block other patents (Torrisi et al., 2016). This can be problematic where many different organisations hold patents required to manufacture a standardised product (Contreras, 2012). In these cases, a license must be negotiated with each patent holder to meet the standard. At the extreme this leads to a patent thicket where the costs of negotiating licenses become so high as to make production uneconomical (Contreras, 2012). For CPR-protecting innovations, the effects of appropriability and artificial scarcity on diffusion are particularly severe, since much of the inventions in these areas occur far upstream from either marketable products or production processes such that they grant the holder control over access to understanding (Nelson, 2006).

The social loss from restricting knowledge is especially severe in low-income economies. Since the Uruguay round of the World Trade Organisation (WTO) negotiations (1986–94), all WTO members became party to the TRIPs Agreement. These agreements integrated IP protection with global trade rules and globalised pharmaceutical patenting (Shadlen et al., 2020). This allowed pharmaceutical companies to globalise the protections they enjoyed in the US in response to emerging competition from nascent pharmaceutical producers such as India and China (Pistor, 2019). The application of patents has also become more complex, extending IPRs to trade agreements involving a variety of products from agricultural products to advanced technologies (Love, 2001; Shadlen et al., 2020; Campi and Nuvolari, 2015). Yet the benefits of this for low-income economies are far from clear. Models of the welfare impacts of tighter IP regimes indicate that the initial acceleration of innovation in developed economies would be insufficient to compensate less developed economies for its subsequent decline (Helpman, 1993). Although the WTO Doha Declaration reinstated the right of states to use compulsory licensing in times of public health emergencies, these agreements contained significant loopholes. The patent system could still be used to forestall the development of generic drugs by privatising the results of drug trials or allowing exceptions knowing that developing countries lacked the production capacity and import options to make use of the Doha Declaration (Sparke, 2020). A lack of production capabilities remains a key obstacle for developing economies in accessing more advanced vaccines (Smith et al., 2011).

2.2. CPRs, patent stacking and the problem of the anti-commons

For CPRs, too much appropriability works against diffusion. CPRs are subject to the tragedy of the commons (Hardin, 1968). The stacking of patents in technologies in these areas leads to the problem of the anti-commons, where instead of a CPR suffering from overuse, a privatised resource suffers from underuse (Heller and Eisenberg, 1998). These practices impede progress and diffusion by creating too many concurrent fragments of IPRs in potential future products and too many upstream patent owners stacking licenses on top of the future discoveries of downstream users. The high bargaining costs created by fragmented and overlapping IPRs deter researchers from pursuing innovative research in these areas.

There is increasing evidence that the fragmentation associated with the anti-commons problem is at the root of the challenges facing the faster roll out of vaccines. Vaccines are not that attractive to the pharmaceutical industry and account for a small proportion of turnover and high development costs (Blume, 2005). Many pharma companies abandoned vaccination production in the 1960s and 1970s, while public health institutions now make a negligible contribution to research in this area. One of the most serious consequences of this has been recurring vaccine shortages. The WHO (2020) found that 56 out of 132 reporting countries (42 %) reported national stockouts of one or more vaccines.

One of the reasons for this is that the knowledge generation in vaccinological networks has been privatised and is protected by patents (Blume, 2005). Vaccine markets have become more concentrated with four firms (GSK, Pfizer, Merck, and Sanofi) controlling 90 % of global market value while five produce 60 % of global volume (SII, GSK, Sanofi, BBIL and Haffkine) (WHO, 2020: 4). Within these firms the production of vaccines has fragmented and is increasingly outsourced to the contract development and manufacturing (CDMO) industry (Bown and Bollyky, 2021). The CDMO industry is largely concentrated in advanced economies. This has meant that the capabilities for vaccine production are increasingly concentrated within a small number of firms and advanced nations, while the development of new or improved vaccines faces significant barriers in terms of the stacking of licenses.

2.3. Can the patent system be reformed to improve diffusion?

The above discussion reflects the fact that in resolving grand challenges that require rapid diffusion of technologies, the fine tuning of IPR regimes and incentives is likely to have only second order effects since the rates of success in fishing for opportunities depend to a large extent on firm-specific capabilities (Dosi et al., 2006). These firm specific capabilities, especially in many technologies designed to protect CPRs such as vaccine production (e.g., Bown and Bollyky, 2021), tend to be unequally distributed.

If society's objective is to stimulate innovation for solving unresolved

grand challenges through open-source technologies (e.g. Ahn et al., 2019), controversies about the nature and scarcity of inventions are arguably outside the point (e.g. Machlup, 1958). Protecting global CPRs requires rapid diffusion of knowledge that is consistent with the idea of a global knowledge society whereby the more people that use a technology "at the same time the more it tends to grow and to benefit each of its users" (Polanyi, 1944: 65).

Our central argument here is that in the case of network externalities where diffusion is dependent on more people using a technology, offshoots of the patent system such as compulsory licensing (CL), patent pools and pledges must be assessed in terms of their potential to induce the transfer of technologies and production capabilities to low-income countries. One of the main policy tools available to governments to deal with anomalies in the patent system is compulsory licensing. CLs have been used extensively in developed economies across such sectors as software, biotechnology, and pharmaceuticals (Love, 2001). Yet, despite the scale of the health crisis facing many economies, the use of CL by low and middle-income countries has been sporadic (Son, 2019). Hence CL often fails to quicken the diffusion of inventions in the countries where it is most needed. There are a variety of reasons underpinning this, stemming from a reluctance of poorer countries to engage in expensive litigation to the lack of a TRIPS compliant patenting registration system (Love, 2001).

Institutional arrangements that address some of the anomalies in the patent system regarding CPRs, include patent pools and pledges. In a patent pool, patent owners license essential technology to a single agent, who in turn offers a license for the entire pool for a royalty fee, with revenues distributed among participants using a predefined formula (Contreras, 2012). In theory, this addresses the problems of stacking and appropriability, but only if all patent holders participate. A study examining the Eco-Patent Commons, a not-for-profit initiative for pledging green technology patents found that patent sharing alone is not sufficient for uptake without a dedicated coordination system to provide dedicated administrative support and managerial resources to promote the commons (Contreras et al., 2018). Pledges differ from patent pools and cross licensing by conferring benefits on third parties regardless of contribution to the commons and without formal contract. This represents a form of open innovation where the boundary of knowledge and resource exchange is expanded from individuals to a group, introducing a level of tension between altruism and commercial viability (Ahn et al., 2019).

3. A patents taxonomy for global CPRs

In this section we build on the existing literature to specify a taxonomy of patents based on CPR and industry characteristics and the wider policy/regulatory environment.

3.1. Global common pool resources and patents

We start by considering theoretical issues regarding technological progress and innovations designed to protect global CPRs. Even when there are known technological remedies for global CPR problems, the potential protection of CPRs may not be realised. Technological change and invention have created many innovations that have the potential to protect CPRs but there are significant challenges in effecting timely diffusion. For example, hybrid electric vehicles (HEV) have been in commercial production since 1997 and emit approximately half the GHG of comparable vehicles powered by internal combustion engines (ICE). Swift adoption and diffusion would have significantly reduced carbon emissions, yet some 25 years after their market debut, the global share of HEV vehicles was only around 10 % (comprising 5 % Full HEVs and 5 % Mild HEVs) in 2021.[4] Consumers and economies remain locked-in to pure ICE vehicles. Similarly, vaccines to protect against COVID-19 have been approved since December 2020 but despite considerable efforts, diffusion has been slow. Initially, COVAX in partnership with WHO and GAVI, set a target of 20 % coverage by the end of 2021, that was subsequently increased to 40 % with an additional target of 70 % of the adult population in all countries by mid-2022. However, even the most modest targets for vaccine rollout have not been met with consequent negative effects on public health. Watson et al. (2022; p. 1298) estimate that had the COVAX 20 % and 40 % targets been achieved, around 680,000 deaths would have been avoided in low- and low-middle-income countries. These examples suggest that we need greater understanding of why, in the presence of potential solutions to solve CPR problems, it remains difficult to implement them in a timely manner.

A key to unravelling this conundrum lies in understanding what Ostrom (1990) and Ostrom et al. (1994) termed the *CPR dilemma*. The *CPR dilemma* is a situation characterised by the coexistence of two conditions: (i) suboptimal outcomes; and (ii) coordinated outcomes that are Pareto superior and feasible (Ostrom et al., 1994; p. 16). This raises the question of what institutional arrangements enable attainment of optimal outcomes and whether these emerge from interactions between players or whether they require top-down regulation, or a combination of both.

Resolving the CPR dilemma requires identifying the nature of the problem, technological solutions *and* understanding the institutional arrangements that could enable society to reach efficient outcomes. We use Ostrom's framework of the CPR dilemma to shed light on the institutional arrangements that can help resolve global CPR problems in the case of innovation diffusion.

To untangle these issues, we adopt the approach suggested by Biagioli (2019) who advocated an industry-specific approach that assesses the pros and cons of patents in specific industry contexts. We extend the idea of a more nuanced approach and combine analysis of industry characteristics and CPRs using the concept of the CPR dilemma, to derive a taxonomy of patents for innovations according to the degree of protection they afford global CPRs. In the following discussion we show how patents and industry characteristics may combine to exacerbate CPR dilemmas. To illustrate our theoretical arguments, we consider them in the context of the vehicles and vaccine sectors. These sectors form the basis of our case studies in Section 4.

3.2. CPR dilemmas: vaccines and electric vehicles

The diffusion of vaccines can be analysed as a CPR dilemma combined with positive network externalities. Prior to the successful invention of COVID-19 vaccines, governments made Advanced Purchase Agreements (APAs) that helped fund R&D *and* contracted pharmaceutical companies to supply an agreed number of doses in the event of vaccine approval by public health agencies. National governments faced two strategic choices: (i) to make bi-lateral Advanced Purchase Agreements (APA) with pharmaceutical companies; and/or (ii) to participate in multilateral purchase schemes, such as COVAX, designed to diffuse vaccines more equally and rapidly across countries (McAdams et al., 2020; Duke Global Health Innovation Center, 2020; John Hopkins Corona Virus Resources Center, 2020). These two options can be viewed as individual and cooperative strategies where the cooperative strategy facilitated via COVAX has the advantage of: (i) encouraging rapid and widespread diffusion; (ii) preventing vaccine hoarding; and (iii) avoiding a situation where rich countries pre-order many times their required number of vaccines, thereby limiting supply to poorer countries.

An additional twist in the case of anti-viral vaccines is that vaccine diffusion is subject to network externalities. Rapid diffusion yields a positive network externality, while slower diffusion produces negative network effects: the lower the proportion of the population that is vaccinated the lower the benefit to vaccinated individuals and the greater the chance of virus mutations. In short, the speed of diffusion

[4] Data from EV Volumes (2022).

affects the efficacy of the invention.

In contrast to the cooperative strategy offered via COVAX, countries could choose to go it alone and strike bi-lateral APAs with pharmaceutical companies. The CPR dilemma predicts that in the absence of commitment to the cooperative strategy by all players, unenlightened self-interested behaviour by national governments results in an outcome that is inefficient compared to the coordinated outcome of more rapid diffusion across countries. Moreover, under the non-cooperative strategy, lower levels of vaccination allow the virus to circulate in the unvaccinated population and to mutate leading to 'vaccine escape' and negative network externalities that undermine vaccine efficacy. It is evident that anti-viral vaccines are subject to complex CPR problems which require robust institutional arrangements to resolve. The fact that slow diffusion undermines vaccine efficacy suggests a clear theoretical rationale for an *automatic* patent waiver for anti-viral vaccines during a pandemic.

It is tempting to think that this is a special case that arises in the case of vaccines and pandemics but does not have wider applications. However, similar CPR dilemmas arise in the case of hybrid (HEV) and battery electric vehicles (BEV). The vehicles sector is subject to significant economies of scale making it hard for new technologies to break through. Three problems combine to prevent the diffusion of HEVs and BEVs which together comprise the electric vehicle market (EV). First, economies of scale in vehicle production make it harder for new technologies to compete with existing ICE technologies that are producing at minimum efficient scale (MES). In essence, there is a coordination problem that requires consumers and/or producers to switch together to enable EVs to reach MES and compete with conventional ICE vehicles on cost/price. Second, production is subject to nested economies of scale problems in the supply chain. The main cost of EVs is the cost of the battery packs, and battery production is also subject to significant economies of scale (Mauler et al., 2021). Finally, in the case of BEVs (as opposed to HEVs) there is lock-in to conventional vehicles caused by well-established networks of fuel stations and the absence of comprehensive networks of EV charging points. This network externality reduces the benefit of owning a BEV and creates 'range anxiety' that limits demand. Patents exacerbate these three problems since they raise costs in the supply chain and in the vehicles market. Moreover, because patents slow diffusion of BEVs and charging points they reduce positive network externalities and the *use value* of BEVs. EVs also illustrate the problem of patent stacking and the anti-commons discussed in Section 2, as patents play an extensive role throughout the vehicles supply chain. Theoretically, there is a case for voluntary institutional arrangements to waive patent fees in the case of EVs (as per Toyota's voluntary waiver in 2019), while in the case of BEVs subject to network externalities there is a case for a formal patent waiver to resolve the CPR dilemma.

In Table 1 we combine our forgoing analysis of the CPR dilemma and industry characteristics to specify a taxonomy which categorises innovations according to their impact on global CPRs. The taxonomy defines 4 categories of impact arising from the interaction of a set of CPR characteristics and a set of industry characteristics: *CPR Negative*; *CPR Neutral*; *CPR Positive*; and *CPR Positive Plus Network Externalities*. Different categories have different implications for patents policy, technology transfer and regulatory policies.

CPR Negative deals with innovations that potentially have a negative impact on CPRs. In this case the speed of diffusion has no impact on the efficacy of the innovation and slower diffusion reduces the detrimental effect on CPRs. An example of such an innovation is fracking which may contaminate groundwater and releases methane gas that can remain a highly potent atmospheric pollutant for up to 20 years. In a study of hydraulic fracturing technology, Cahoy et al. (2013) have argued that patents have prevented the experimentation necessary to understand fracking's global impact on CPRs. They advocate relaxation of patent law to allow third party testing to determine the environmental and public health effects. *CPR Neutral* covers the case of innovations that have neutral or insignificant impact on CPRs. This category covers a vast array of innovations for public and private goods and probably represents how patents are often envisaged i.e. without reference to CPRs, though our argument is that this is just one, albeit it probably the largest, category of innovations in this taxonomy. In this case, economies of scale in production and patent stacking have negative effects on diffusion but there is no specific impact on CPRs.

The *CPR Positive* category considers the case of innovations that have the potential to protect CPRs, for example, CFC replacement gases that are less damaging to the ozone layer, or HEVs that reduce carbon emissions compared to petrol and diesel ICE vehicles. In this category, the speed of diffusion is positively related to the beneficial effects on CPRs. Industry characteristics affecting the speed of diffusion include economies of scale in final production and economies of scale in the supply chain. High fixed costs of production in industries such as vehicles implies that production based on newer, cleaner technologies has higher unit production costs compared to existing technologies that are already at minimum efficient scale. As a result, it can be harder for more efficient technologies to overcome barriers to entry. Scale effects may also reside in the supply chain. Batteries are the main cost component of HEVs and EVs and battery pack production is also subject to significant economies of scale, slowing diffusion. Coordination both on the supply side or the demand side that expands production can speed up diffusion by putting new technologies on an equal cost footing with incumbent technology. For example, policies that shift consumer demand away from ICE vehicle to EVs can lower the unit cost of EVs.

In terms of patents, vehicle manufacturers have used voluntary patent sharing and waivers to resolve the CPR dilemma. In 2015 Tesla pledged to share its EV patents (provided the users agreed to share theirs) on the grounds that the real competition was not with other EV producers/technologies but with existing ICE technologies that dominate the market. In April 2019 Toyota made 24,000 EV-related patents freely available to its competitors, waiving the right to royalty fees and offering to provide related R&D services (tacit knowledge) on a fee basis. Toyota cited environmental concerns in its press announcement, but as discussed above the hallmark of the CPR dilemma is that both individual actors (firms) *and* society benefit from coordinated actions. The benefit to Toyota from encouraging the development of the EV market is greater economies of scale in production, including in the battery supply chain which reduce unit costs while also giving a fillip to the growth of BEV charging networks.

This last point leads us to the *CPR Positive Plus Network Externalities* category: innovations that have positive effects on global CPRs and also generate positive network externalities. A significant factor holding back consumer demand for BEV is 'range anxiety' associated with thin and patchy charging point networks. An expanding BEV market encourages the growth of charging networks and increases the use-value of BEVs. Similarly, rapid diffusion of vaccines increases their efficacy and the benefit to users, while slower diffusion undermines their effectiveness. This category of innovations that protect CPRs and incorporate network externalities is therefore a special case where patents that slow diffusion of such innovations also undermine their effectiveness, their use value to consumers and their potential positive impact on CPRs.

4. Case study evidence from two natural experiments

Drawing on the above insights we examine pairs of case studies of innovations that protect CPRs and the factors shaping their successful diffusion. Each pair has been selected to embody a natural experiment.

4.1. Natural experiment 1: vaccines pre-TRIPS (polio) and post-TRIPS (COVID-19)

An important case of technology diffusion prior to TRIPS for an innovation characterised by significant positive impacts on CPRs with network externalities is provided by the roll out of Jonas Salk's unpatented polio vaccine. This case illustrates the importance of cooperative

Table 1
Innovations, patents and CPRs: Towards a taxonomy.

Innovations categorised by potential impact on global CPRs relative to *status quo*	Factors determining impact on CPRs			Characteristics affecting diffusion			Example technology	Policy implications		
	Is the nature of CPR problem time critical?	Impact of speed of diffusion on CPRs and on the efficacy of technology	Coordination needed to resolve conflict between individual and collective interests (CPR Dilemma)	Economies of scale in production and geographic concentration of production	Economies of scale in supply chain and stacking of patents	Extent of tacit knowledge vs codified knowledge		Patent policy	Technology transfer policies	Regulation
1. *CPR Negative*Innovation has significant negative impact on global CPRs	Yes	Slower or no diffusion protects CPRs	Coordination desirable to limit or restrict use of technology	Economies of scale slow diffusion reducing potential negative impact on CPRs	Stacking of patents will have positive effect on CPRs	No need to transfer tacit knowledge	Fracking	Patents beneficial as they slow diffusion with positive effects on CPRs, but may also prevent testing and obscure impact on CPRs	Not beneficial for society as this technology has negative impact on CPRs	Regulation needed to restrict diffusion or ban use
2. *CPR Neutral* Innovation has neutral or insignificant impact on global CPRs	N/A	None	No	Economies of scale slow diffusion but with neutral impact on CPRs	Stacking of patents will slow further knowledge development	Tacit Knowledge sharing helps diffusion but no significant effect on CPRs	Turntable, food mixer	Patents slow diffusion but with no or insignificant impact on CPRs	Not needed to protect or enhance CPRs	Not needed to protect or enhance CPRs
3. *CPR Positive* Innovation has significant positive impact on global CPRs	Yes	Slower diffusion reduces potential positive impact on CPRs	Timely coordination needed to promote technology sharing and/or coordinate shifts in demand	Economies of scale slow diffusion and have negative impact on CPRs	Stacking of patents has negative effect on CPRs e.g. patents on batteries increase price with knock on effects in vehicles industry	Sharing of tacit knowledge throughout supply chain needed to speed diffusion	Non-ozone depleting CFC gases, hybrid electric vehicles (HEV)	Patents slow diffusion and undermine potential protection of CPRs; institutional solutions needed e.g. multilateral fund to cover fees, patent waiver or pledge, including in supply chain	Transfer of tacit knowledge needed especially to low- income countries	Time limits, incentives, and other public policies needed to speed transition to superior CPR-protecting technologies
4. *CPR Positive Plus Network Externalities* Innovation has significant positive impact on global CPRs including via Network Externalities	Yes, with critical tipping points	Slower diffusion diminishes CPRs and may reduce the efficacy of the invention e.g. virus mutates in unvaccinated population creating resistant strains; or lack of charging points reduces use-value of battery electric vehicles (BEV)	Yes, urgent coordination required	Economies of scale and geographic concentration of production inhibit or prevent diffusion over time and space	Stacking of patents will slow diffusion and knowledge transfer	Sharing of tacit knowledge at more than one stage of production needed to speed diffusion	COVID-19 vaccines, battery electric vehicles (BEV)	Patents slow diffusion *and* undermine efficacy of inventions; immediate waivers needed to support product diffusion, may also need waivers & other actions to unstack supply chain patents	Transfer of tacit knowledge needed, especially to low-income countries	Time limits and/or public policies needed to support expansion of production capacity and networks e.g. of electric vehicle charging points or public heath infrastructure to administer vaccines

type buy in by state health authorities and building capacity via the exchange of scientific knowledge. The case is especially relevant since it involved a vaccine technology that had become suboptimal as epidemiological profiles changed (Blume, 2005). The case has relevance to COVID-19 since although many countries have been successful in eradicating polio by the 1970s, the disease remained prevalent in many developing countries during the 1980s (Ochmann and Roser, 2017). Central to dealing with emerging variants has been the ability to adapt vaccine production and administration in affected areas (Goldblum et al., 1994).

Following a large outbreak of polio in the 1950s the Israeli government scaled up industrial production of Salk's polio vaccine. Israel, then a developing country, lacked capabilities in this area of vaccine production. In 1955 Natan Goldblum, director of the Israeli government virology department, was sent to Salk's laboratory in Pennsylvania to study Salk's methods (Blum et al., 2010). Israel emerged in 1957 as the third country in the world after the US and Denmark to produce a polio vaccine.

Israel's efforts to produce a polio vaccine are remarkable for two reasons. First, they led to a rapid drop in case numbers that replicated those achieved in high-income economies such as the US (Fig. 1). The number of polio cases in Israel dropped from an annual average of 650 in the years 1952 to 1956 to 57 in 1957 and 38 in 1960 (Blum et al., 2010; p. 2074). While the large drop in 1957 was like other countries in the region without capacity, and the potency and coverage of the vaccine, even in 1958, may have still been weak, by 1959 the impact of the vaccine on incidence was clear (Davies et al., 1960). Indeed, subsequent outbreaks were largely confined to the non-vaccinated and largely non-Jewish migrant populations and having in-country capacity helped innovate vaccination delivery for these populations (Fig. 1). Secondly, and more crucially in terms of the diffusion of knowledge, the production of the patent free vaccine stimulated an increase in research and diffusion of tacit knowledge on poliomyelitis during the periods surrounding outbreaks (Fig. 2). Israel saw an increase in publications and citations indicating knowledge diffusion (Fig. 3). The results of this included the production of an oral vaccine to treat an epidemic in 1961 which primarily affected the non-Jewish unvaccinated population and Goldblum's own career which saw him publish more than 50 papers on poliomyelitis and engage in international collaboration on infectious diseases (Goldblum et al., 1994; Blum et al., 2010). There is similar evidence of knowledge diffusion from other countries that adopted Salk's vaccine. Investment in Salk's vaccine by the Dutch and Danish health authorities led to innovations that addressed local production bottlenecks, the production of an enhanced vaccine, and public investment in vaccine research that would not otherwise have been carried out by private companies (Blume, 2005).

Potential counterfactual cases of developing countries in the region who did not benefit from technology transfers include Lebanon and Egypt. From 1966 to 1970 average reported cases increased to a yearly average of 270 in Lebanon and 1665 cases for Egypt (Swartz, 2008: 75). Lebanon achieved polio free status in 1994, but experienced subsequent outbreaks of wild polio virus (Alawieh et al., 2017). Egypt did not eradicate the virus until the mid-1990s following the implementation of global vaccination strategies and establishment of WHO reference laboratories as part of the Global Polio Eradication Initiative (Aylward et al., 1997). The latter represents a type of cooperative strategy without technological capacity building. The evidence here indicates that this type of cooperative strategy is less optimal and slower than one with full technological capacity building.

4.1.1. *Vaccine development and diffusion for COVID-19 post-TRIPS*

The announcement by the WHO in January 2020 that COVID-19 constituted a health emergency of international concern triggered a race against time to create a vaccine. University scientists and pharmaceutical companies worked in a regulatory environment that supported fast-tracking of clinical trials with significant public funding both in the form of direct R&D subsidies and advanced purchase agreements (APAs). Governments of many advanced and middle-income countries struck individual APAs with pharmaceutical companies on the basis that if the vaccine was successful they would receive the contracted number of doses ahead of other buyers, but if the vaccine failed to attain approval, the companies would keep the money from the APA contract (John Hopkins Centre, 2020). This combination of policies: fast tracking of clinical trials; R&D subsidies; and guaranteed markets for successful companies significantly reduced risk and encouraged investment in vaccine development. The development of COVID-19 vaccines in less than 1 year was a remarkable collaborative achievement.

The picture regarding diffusion is less rosy. The case of South Africa's fight against COVID-19 illustrates how, even in developing countries with vaccine manufacturing capacity, patents on COVID-19 vaccines had a negative impact on their efforts to produce vaccines and respond to the pandemic. At the onset of the pandemic, South Africa was, together with Morocco, Tunisia, Egypt and Senegal, one of the few African countries with Covid vaccine manufacturing capacity (WHO Africa, 2022). Despite this, South Africa has become one of the countries with the highest number of Covid cases and deaths on the African continent and the world, as can be seen in Fig. 4(a) and (b) (The Economist, 2021; Roser et al., 2022). One of the reasons is the delay in vaccination.

In October 2020, South Africa called for the WTO to waive intellectual property rights on Covid vaccines, tests and treatments for (at least) three years - a proposal that was opposed by the pharmaceutical industry and many high-income countries (Huber, 2022). In June 2021, the WHO and a South African consortium comprising two pharmaceutical companies and the Africa Centres for Disease Control and Prevention established Africa's first COVID-19 mRNA vaccine technology transfer hub in South Africa (WHO, 2021). This was part of a pilot project aimed at providing low and middle-income countries with the know-how required to produce COVID-19 vaccines (Roelf and Steenhuysen, 2022). South African biotechnology startup *Afrigen Biologics and Vaccines* sought to replicate *Moderna*'s mRNA vaccine, following Moderna's commitment not to enforce their COVID-19 vaccine patents during the pandemic. *Afrigen* asked *Moderna* to share its vaccine technology, but Moderna refused. Despite this, researchers at *Afrigen* managed to reverse engineer their vaccine and plan to get vaccine approval in 2024 (Langreth and Decker, 2020; Roelf and Steenhuysen, 2022; Walker, 2022). The process of making a Covid vaccine would have taken only a year with the help of Moderna (Davies, 2022).

The nature of the APAs resulted in middle and high-income countries securing most available vaccine doses, while low-income countries struggled to gain access. By May 2021, one month before the establishment of the WHO's mRNA vaccine technology transfer hub, less than 1 % of the South African population had been fully vaccinated against COVID-19 (Mendez, 2021). This share has since increased to 32 %, but was still significantly lower than that in Europe (66 %) and the US (67 %) (Roser et al., 2022).

As predicted by the CPR dilemma, vaccine supply has been cornered by bilateral country deals at the expense of multilateral deals designed to provide more equitable access. One of the biggest contrasts with the Polio case is the fact that privatisation of knowledge under TRIPS makes it much harder to diffuse production, so that a patent waiver without the necessary support for open innovation and technology transfer would mean that the ability to diffuse vaccine production is severely limited. In June 2022 a limited patent waiver was agreed by the WTO but it is not the broad waiver proposed in October 2020 by South Africa and India covering COVID-19 vaccines, tests and treatments and the agreed text has been criticised as “a watered-down waiver of one small clause of the TRIPS agreement relating to exports of vaccines. It also contains new barriers that are not in the original TRIPS agreement text.” (Oxfam, 2022).

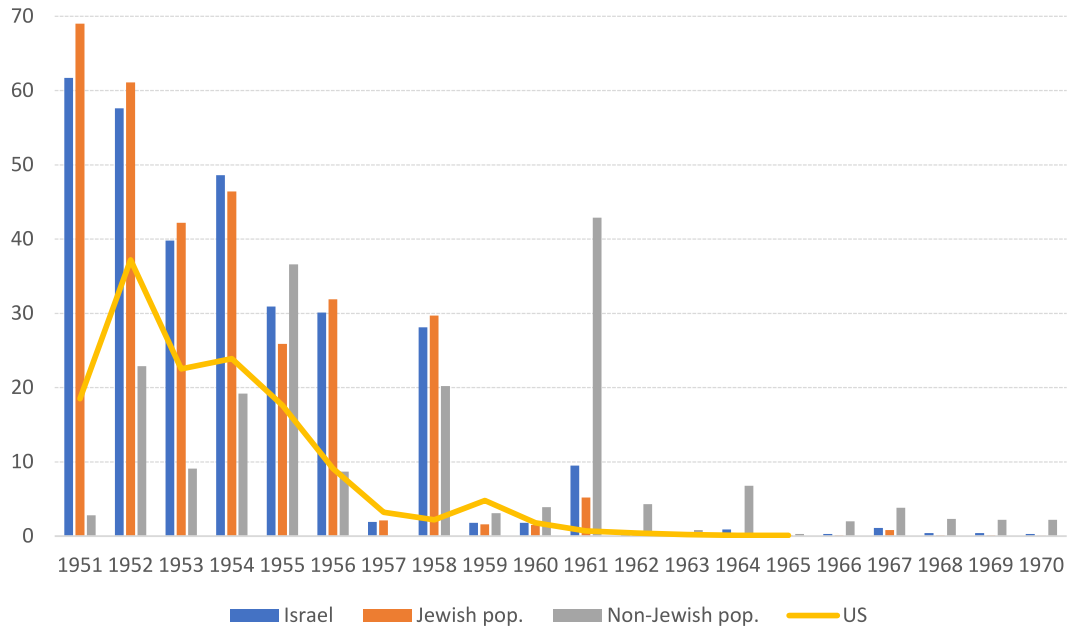


Fig. 1. Polio case rate per 100,000 population: Israel (Jewish and non-Jewish populations) vs United States (1951–70).
Source: US data is from US Public Health Reports (1967: 419). Israeli data from Swartz (2008).

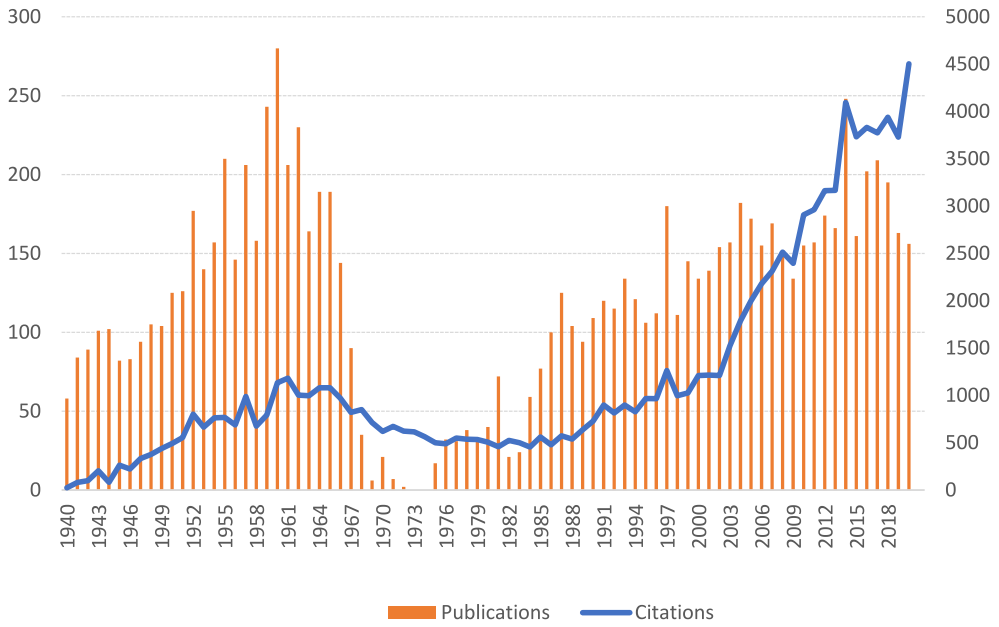


Fig. 2. Total publication (LHS) and citation (RHS) data for poliomyelitis (1940–2020). Notes: The results are based on citations search of the Web of Science database for scientific publications on poliomyelitis.

4.2. Compulsory licensing under TRIPS and access to HIV/AIDS drugs

A third regulatory environment that can be considered concerns compulsory licensing (CL). CL recognises the CPR dilemma by allowing the use of a patented invention without the patent owners' consent in order to improve access to essential inventions, for example, pharmaceutical drugs (e.g. Stavropoulou and Valletti, 2015). CL was introduced in 1995 as part of the TRIPS Agreement. A CL is not the same as a patent waiver as some compensation is paid to the license owner and CLs are restricted to domestic consumption. Moreover, countries seeking a waiver must demonstrate that they have tried to strike a license deal with the patent holder but have been unsuccessful. Hence, CL takes some time to initiate.

The diffusion of HIV treatments using CLs offers a case study of technology diffusion post TRIPS for an innovation characterised by significant positive impacts on CPRs with potential network externalities. In developing countries CLs have been used with the aim of improving access to HIV/AIDS drugs (Son, 2019). In 2021, some 38 million people globally were living with HIV; and most (28 million) had access to antiretroviral drugs (UNAIDS, 2021). In 1999, almost as many people lived with HIV (33 million), but the majority had no access to treatment (Berman, 1999). Empirical evidence shows that CL has played a crucial role in improving access to HIV/AIDS drugs in developing countries by reducing their prices (e.g., Urias and Ramani, 2020). Using a sample of 34 low and middle-income countries between 1995 and 1999, Borrell and Watal (2002:5) found that switching all HIV/AIDS

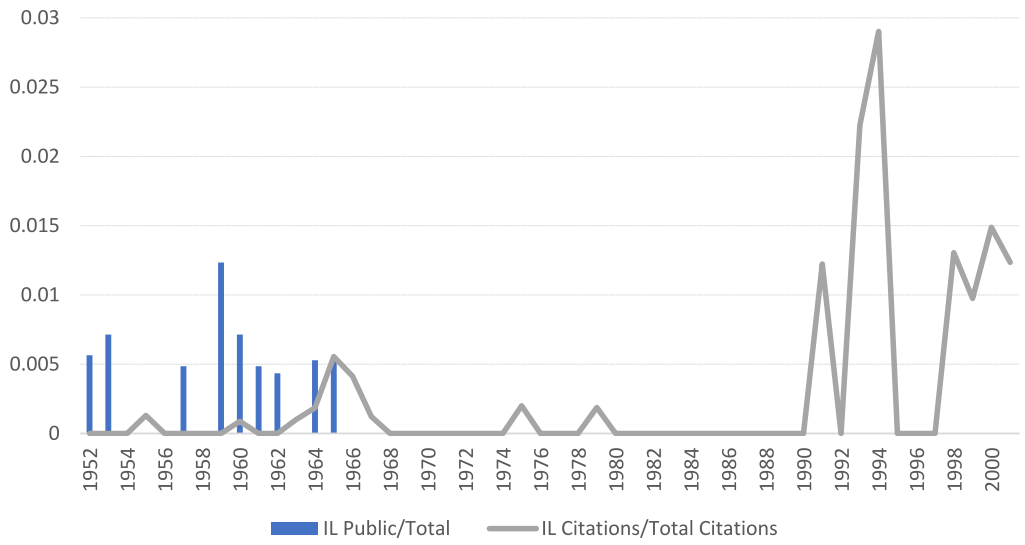


Fig. 3. Publication and citations on Israel (IL) and poliomyelitis as % of total (1952–2001). Notes: Results are based on citations search of the Web of Science Core Collection database of scientific publications on the topic of poliomyelitis and Israel for the years 1952–2001.
(Source: *Web of Science Core Collection*.)

drugs from a patent to a no patent regime would have increased access by at least 30 %.[5]

But CL is not a silver bullet. CLs have proved to be a slow way of achieving coverage and diffusing knowledge of such treatments as Antiretroviral Therapies (ART). By 2005 ART coverage for patients living with HIV had reached 50 % in the Euro Area (a proxy for developed countries) but stood at 3.6 % in Sub Saharan Africa (Fig. 5). By the mid-1990s, around the same time as the introduction of CLs, significant advancements had already been made in combination therapies including US approval of ARTs. In some instances, the medicines patent pools for promising HIV treatments such as Dolutegravir have proved effective in achieving diffusion. Dolutegravir was licensed in 2014 and by the time it was added to WHO's list of essential medicines to be made available at low cost in 2017, "several patent pool sub-licensees had filed for approval of generic versions" (Burrone et al., 2019: 576).

As discussed by Moser (2013), when using CL, countries do not have the knowledge transfer from the scientist and skilled workers who developed and implemented the original innovation. Fig. 6 illustrates the slow diffusion of such knowledge from high to low-income economies. Although breakthroughs in ART resulted in a jump in publications on the topic, it was not until the mid-2000s that there was a growth in research on ART relating to their application in Africa. In addition, facilitating timely, equitable and affordable access to health products requires also overcoming constraints in the supply chain of inputs and the diffusion of knowledge to increase manufacturing capacity in multiple countries to harness technology and innovation for the common good.

4.3. Natural experiment 2: environmental technologies for CFC gases under the Montréal Protocol and low/zero emission vehicles under TRIPS and the Paris Agreement

In our second natural experiment case study we compare the diffusion of two environmental advancements: the reduction and near elimination of CFC gases and the diffusion of low/zero emission vehicles to replace pure ICE vehicles.

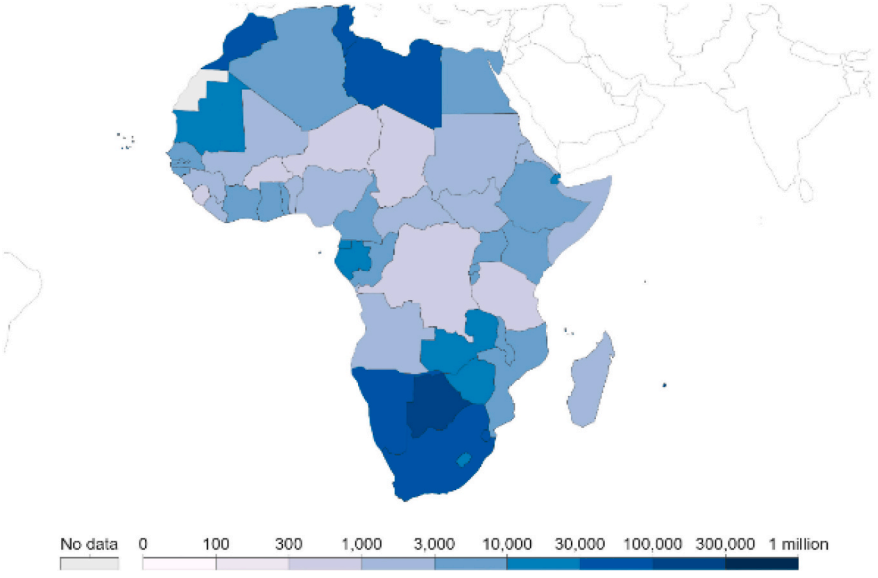
4.3.1. IPR and CFC gases: the Montréal Protocol

The Montréal Protocol (MP) introduced in 1987 is the only Environmental Protocol ratified by all 198 UN Member states and is widely regarded as the most successful. The agreement required developed countries to cut CFC gas consumption by 50 % between the baseline reference year (1986) and June 1999. In the event, the 50 per cent target was met by 1991/2, around 8 years ahead of schedule – see Fig. 7. The success of the MP is due to a number of factors: (i) binding deadlines to phase out the most polluting CFCs; (ii) a robust system for measuring controlled CFC consumption by country; (iii) a multilateral fund that included flexible instruments and incentives to encourage cooperative research and diffusion of replacements for controlled CFC gases; and (iv) explicit recognition of the differences between developed and developing countries (De Sombre, 2000: 49), who were given longer to adjust and financial and technical support. Initially, key players in the industry were sceptical about committing to the Protocol's cooperative regulatory framework however, alternatives were diffused within 5 years and controlled CFC emissions in developed countries were more than halved before falling to zero as shown in Fig. 7.

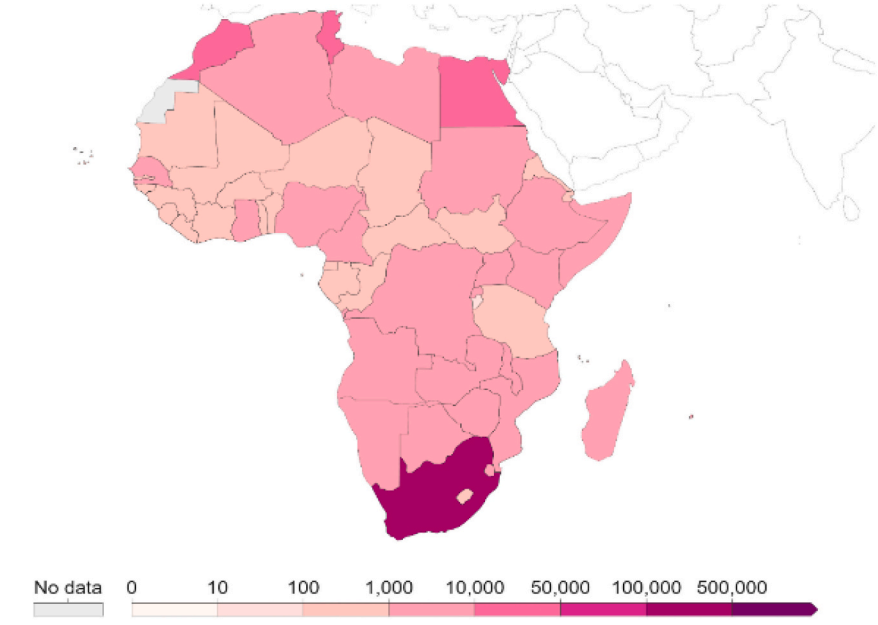
Under the MP over US$3.9 billion was invested in a *Multilateral Fund for the Implementation of the Montréal Protocol* established in 1991 to provide technological assistance supported by strong links between the science base and industry (UNEP, 2021). The Multilateral Fund covered the cost of patents and licensing fees for new technologies and products to replace CFC gases, thus speeding diffusion (UNEP, 2016) by effectively removing IPR-based obstacles.

A central take-away from this case study is that while prior to regulation key players in the industry resisted regulation, for example Du Pont (Moore, 1990), the MP successfully delivered many targets within 5 years by effectively removing the brake on diffusion emanating from patent fees, and by encouraging knowledge sharing and technology transfer via Articles 9 and 10 of the Protocol. After 1995/6 most remaining CFC production was in developing countries who were given a longer time frame as well as technology and knowledge transfer support to help them eliminate CFC gases. The work of the MP is not yet done as some of the replacements for controlled CFC gases emit greenhouse gases (GHG) and regulation is ongoing to find solutions that protect the Ozone layer and reduce GHG emissions. Nevertheless, the MP provides useful guidance on policies to protect CPRs.

[5] Similar conclusions can be found in Borrell (2007), who using the same sample of developing countries for 1995–2005 also found that drug prices were higher under patent regimes.



(a)



(b)

Fig. 4. (a). Cumulative confirmed COVID-19 cases in Africa by 14 August 2022. (Source: https://ourworldindata.org/coronavirus/country/south-africa.) (b). Cumulative confirmed COVID-19 deaths in Africa by 14 August 2022. (Source: https://ourworldindata.org/coronavirus/country/south-africa.)

4.3.2. Low/zero emission vehicles in the absence of a binding UN protocol

4.3.2.1. The case of electric vehicles. The diffusion of BEV and PHEV presents rather differently – see Fig. 8 which shows that in 2019 only Norway had a share in excess of 5 %. This is due to a number of factors including: (1) their higher cost, partly associated with scale effects; (2) their shorter driving range; (3) the required charging time; (4) the need for charging infrastructure; and (5) the failure to internalise the negative effects of ICE vehicles through policy interventions (Barton and Schütte, 2017: 150–151).

Fig. 9 provides data on the shares of EVs for 55 countries in 2022 (January–July). The aggregate global share of all 4 types of EV (including FHEVs and MHEVs) stands at 23 %, a significant improvement on the figure of 10 % in 2019, but there is wide cross-country variation, from Malaysia at less than 1 % to Norway at over 83 %. Norway heads the graph because it has set the tightest timeline (2025) for the phase out of petrol and diesel ICEs. In fact, all of the nations in the top-ten in Fig. 9 have set *clear and near* dates for achieving 100 % sales of EVs, confirming the power of a binding deadline. However, a key difference between the MP which set an internationally agreed timeline for the phase out of controlled CFC gases and the case of electric vehicles is that there is no internationally agreed protocol. As a result, countries have progressed at very different rates even within the broad groupings of developed and developing economies. For example, it is noticeable

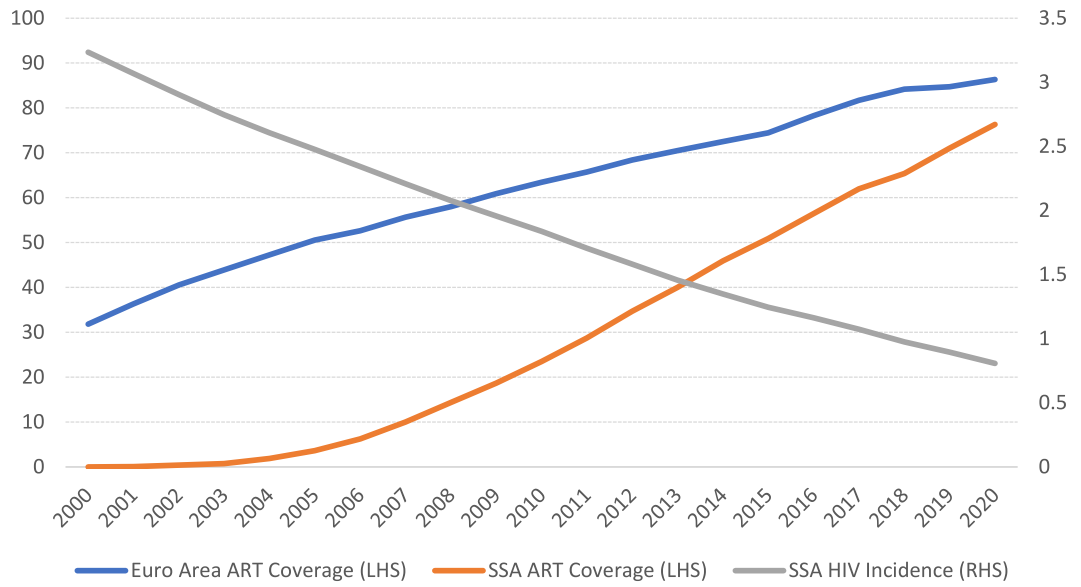


Fig. 5. Incidence of HIV vs antiretroviral therapy coverage (ART) in developed and Sub-Saharan Africa (SSA) countries (2000−2020). Notes: Incidence of HIV is measured per 1000 population. ART coverage is expressed as a % of people living with HIV. The Euro Area is used as a proxy for coverage in Developed countries. (Source: World Development Indicators.)

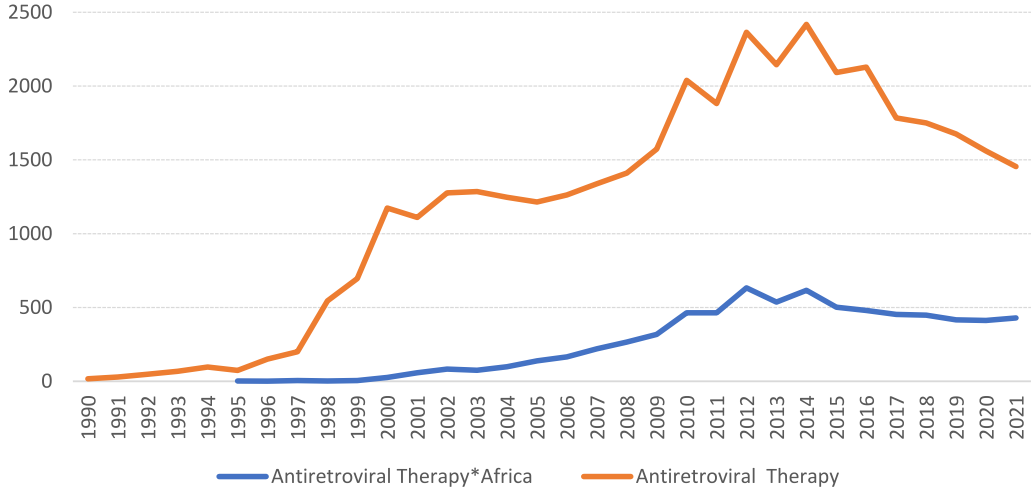


Fig. 6. Scientific publications on ART (1990–2021). Notes: Results are based on citations search of the Web of Science database for scientific publications on Antiretroviral Therapies generally and those relating specifically to Africa.
(Source: Web of Science Core *Collection*.)

that the US is languishing around the bottom third of the table notwithstanding the regulatory lead taken by the state of California on emissions standards. A further difference between the CFC/MP case and the EV case is that the phase out of petrol and diesel cars and the diffusion of EVs has been unsupported by a multi-billion, multilateral fund to transfer technology and pay patent licensing fees, to help bridge the gap across countries.

This leads us to the question of patents. As discussed in Section 3, Tesla announced a patent pledge in 2015, while in 2019 Toyota, the lead player in terms of BEV and HEV R&D, agreed to waive the license fee on 24,000 EV-related patents developed over the past 30 years under a programme led by Japan's Ministry of International Trade and Industry (MITI). Tesla's patent pledge is a hub and spoke arrangement (Tesla benefits from the right to use the patents of any company using its patents), while Toyota's royalty waiver, supported by a fee-based technical assistance programme is a unilateral patent waiver. At the time of the waiver some 50 companies were paying royalty fees to Toyota (FT, 2019) which raises the question of why Toyota would give up this revenue stream. Our analysis in Section 3 indicates that Toyota stands to gain in at least 2 ways. Firstly, via a reduction in battery prices as economies of scale are realised in the supply chain, reducing costs and making it easier for EVs to compete with ICE vehicles (pecuniary economies of scale). And secondly, by the expansion of charging networks as EV sales increase (network externalities). Of course, Toyota may also benefit in terms of corporate social responsibility by meeting its stated objective: "to further promote the widespread use of electrified vehicles." (Toyota, 2019).

Fig. 10 shows the price of lithium-ion batteries used in EVs and its relationship to market size. As can be seen, there has been a significant price fall associated with the rise in sales consistent with pecuniary economies of scale in the supply chain and technological advances (Ziegler and Trancik, 2021). At the same time there have been significant increases in the extent of EV charging networks consistent with positive gains in network externalities, though networks are still

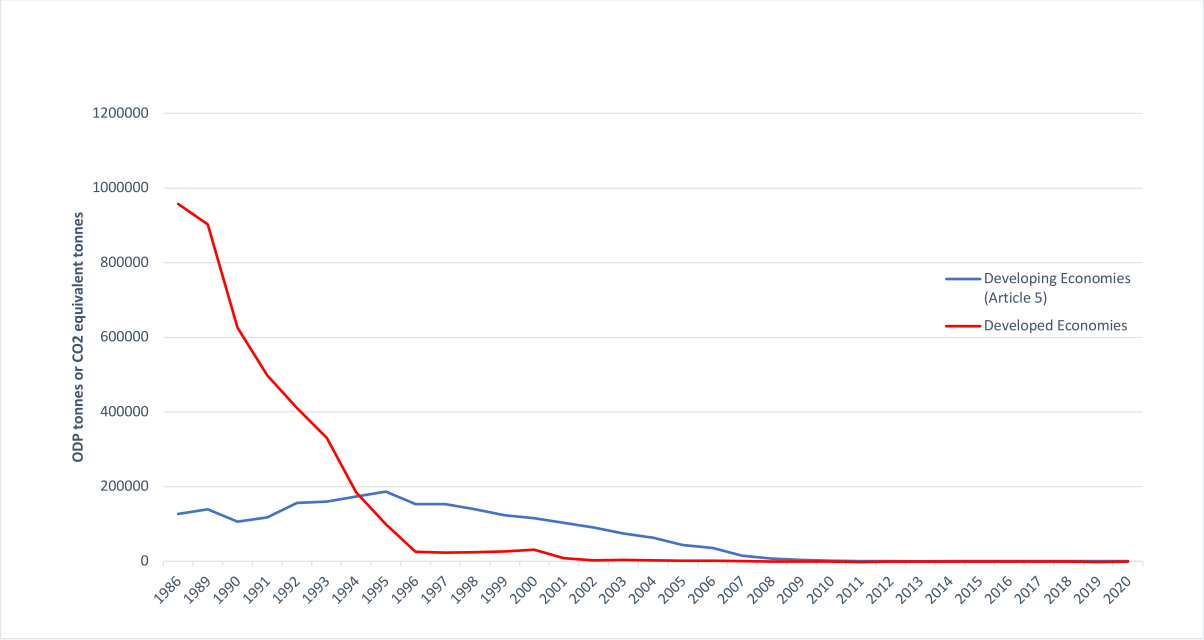


Fig. 7. Consumption of controlled substances under the 1987 Montréal Protocol.
(Source: UNEP Ozone Secretariat (2021).)

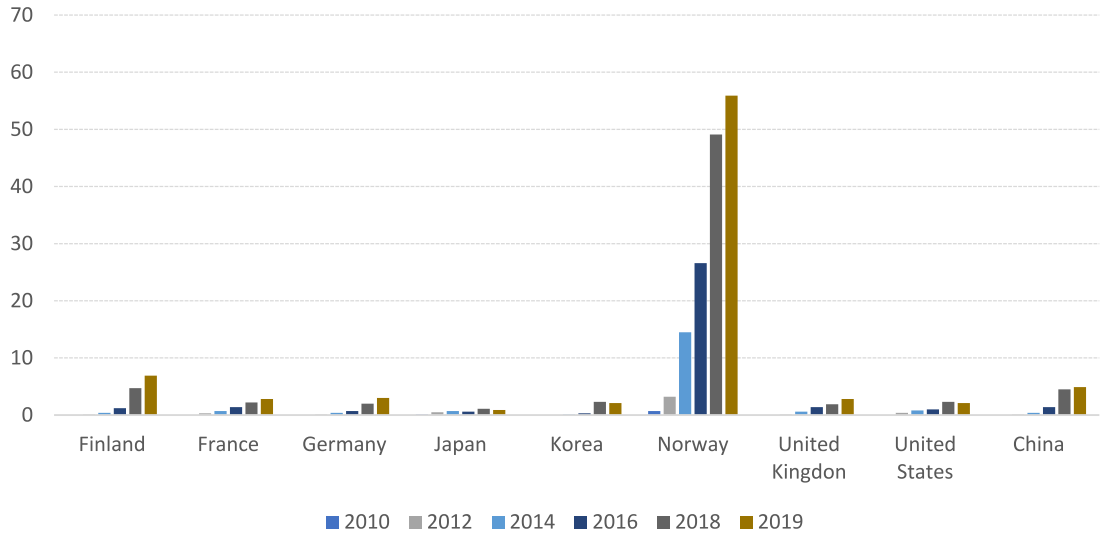


Fig. 8. Market share (%) of electric vehicles (BEV and PHEV) in selected developed and China, 2010–2019.
(Source: Data adapted from IEA (2020; p. 250).)

underdeveloped in all countries.

To explore the effect of the Toyota patent waiver we also look at the sales of non-Toyota EVs compared to Toyota EVs before and after the waiver and test for structural breaks in each group as well as conducting difference in difference analysis. Fig. 11 shows that there is a clear change in trend for non-Toyota global sales of EVs from April 2020 onwards. To test for a structural break, we ran a regression of non-Toyota sales against a time trend and the US price of gasoline and then ran a CUSUM test. The results confirmed a significant structural break in April 2020 one year after the Toyota waiver, which roughly coincides with the time taken to expand production plants in the vehicles industry. Carrying out the same test for Toyota global sales revealed no significant structural break. Fig. 11 shows a very modest upward trend for Toyota sales post April 2020.

Prior to April 2020 Toyota and the rest of the market followed approximately parallel trends satisfying one of the necessary preliminary conditions for difference-in-difference analysis. To conduct this analysis we treat 'global suppliers of EVs excluding Toyota' as the Treatment Group, as they stand to benefit directly from the patent waiver, and Toyota as the Control Group. We carried out difference-in-difference (DiD) analysis for the Treatment Group and the Control Group, pre and post the April 2019 patent waiver. Because of production lags we also conducted the DiD analysis pre-and post April 2020: the main results were unchanged. We estimate the following equation:

$$S_{idt} = \alpha + \beta_1 W_d + \beta_2 D_t + B_3(W_d{}^*D_t) + \beta_4 G_{idt} + \varepsilon_{idt}$$

where S is global EV sales, W is a dummy variable that takes the value of 1 for the Non-Toyota Manufacturers who may potentially benefit from the waiver, D is a time dummy that takes the value of 1 post-waiver and G is the $ price of gasoline in the US as a control variable for the cost of

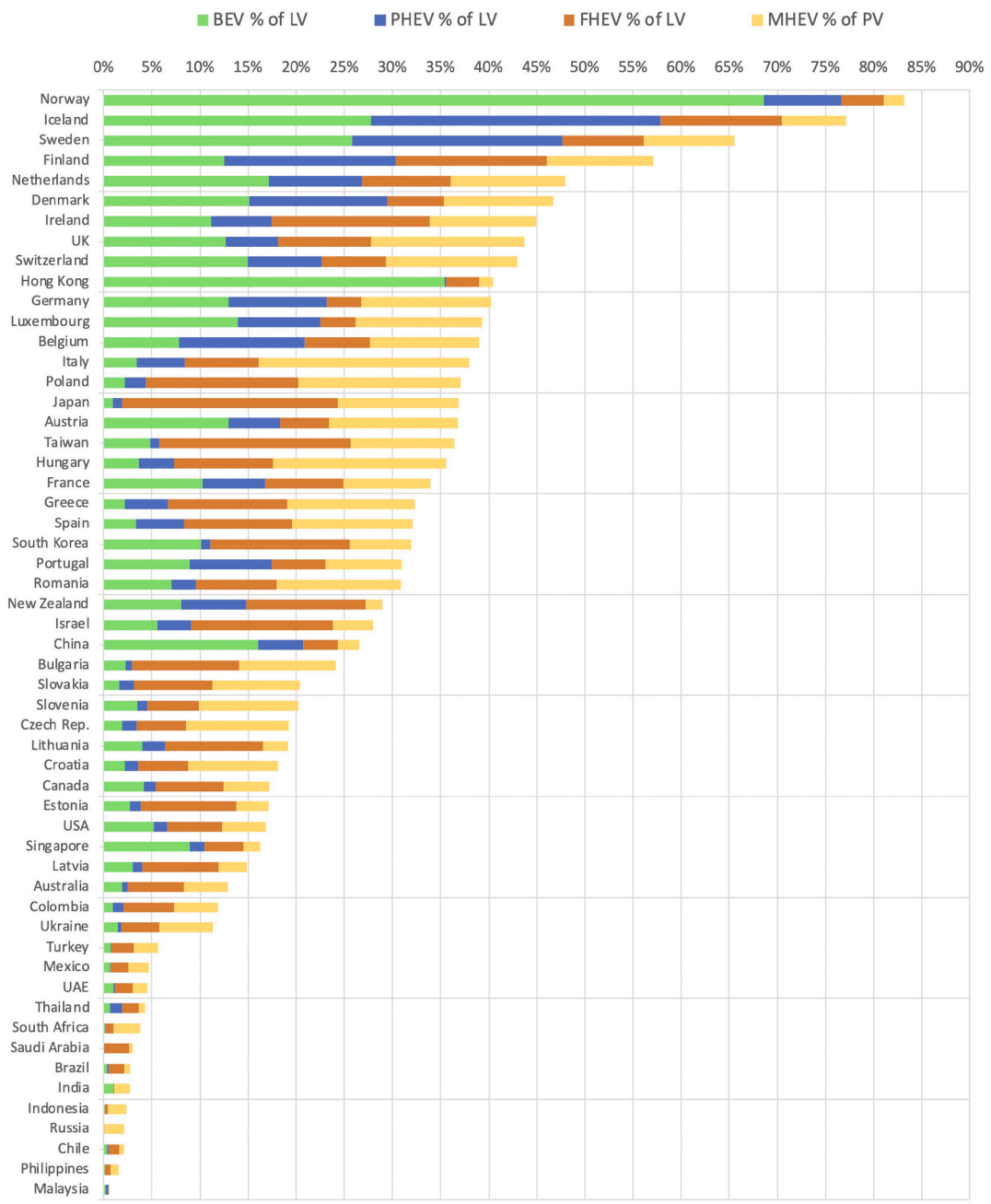


Fig. 9. Market shares of new BEV, PHEV, full-HEV and mild-HEV vehicles, 2022. (Source: EV Volumes.)

fuel. The US price has been chosen as it is relatively unaffected by taxes.

Tables 2 and 3 present the results from our DiD analysis and regression and provide statistical evidence to support the hypothesis that the Treatment Group benefited from the patent waiver: the coefficient on the difference in difference variable W*D is positive and significant at the 1 % level.

The results should be treated as providing only indicative support for a positive waiver effect rather than clear confirmation for the following reasons. Firstly, within the Treatment Group we do not know which companies used Toyota's patents and/or technical support as this information is not available, though we do know that 50 companies were paying Toyota patent fees pre-waiver (FT, 2019). Those companies using Toyota's patents and expertise would receive direct benefits, while those not doing so would only benefit from indirect effects (cheaper battery prices and richer EV charging networks). Indirect effects may underlie the gentle rise in Toyota sales post April 2020. Secondly, we may not have controlled for variables that affect the treatment group, but not Toyota. While many regulatory changes affect Toyota and the Treatment Group equally, we have not controlled for differences in the geographic markets of Toyota and the Treatment Group, though with international trade and Toyota's global reach this may not be a critical factor. Nevertheless, Fig. 11 does show that global sales by non-Toyota manufacturers increased significantly post waiver while Toyota sales showed only a very modest increase, as expected from our analysis in Section 3. Indeed, most of the growth of the non-Toyota EV market has occurred post waiver. While further research is needed there is tentative evidence to support the case for an internationally agreed waiver for EVs as set out in our discussion of the categories *CPR Positive* and *CPR Positive Plus* in Table 1.

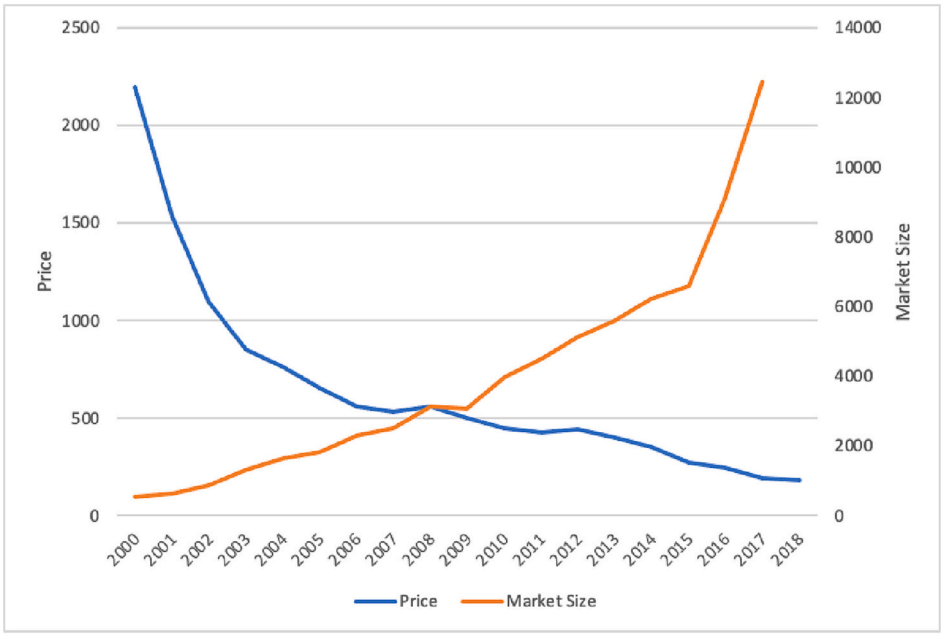


Fig. 10. Representative price and market size of lithium-ion battery cells.
(Source: Ziegler and Trancik (2021b).)

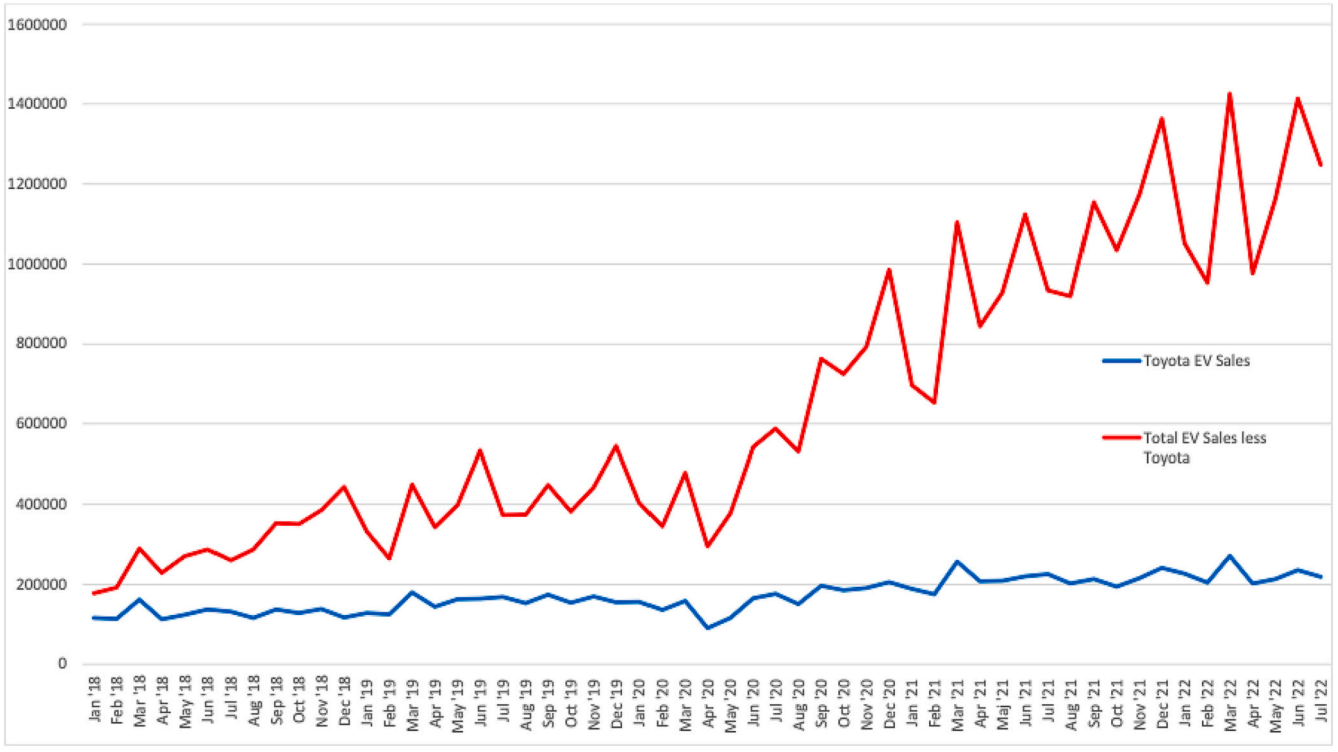


Fig. 11. Global sales of EV vehicles (HEV, PHEV, BEV, FCEV) by Toyota and by all manufacturers *less* Toyota sales.
(Data source: EV Volumes.)

5. Policy implications and concluding comments

The COVID-19 pandemic and the global climate crisis have highlighted the need to consider the impact of patents on global CPRs. This was forcefully illustrated in how the rapid development of vaccines represented a triumph for publicly funded research but the lack of coordination to manage IPRs, technology transfer, financing and production, thwarted diffusion and led to higher excess deaths and greater losses in economic output (Lancet Commission, 2022). Our contribution is to set out a taxonomy that could be incorporated into policy decisions on the granting and waiving of patents where certain conditions relating to global CPRs and industry characteristics are met. We advocate its use to inform a more granular approach and one that recognises that for technologies to protect global CPRs patents can be counterproductive because slowing down diffusion undermines the very efficacy of the invention itself.

Table 2
Difference in difference analysis: Sales pre & post waiver.

	Toyota (control)	All manufacturers except Toyota	Counterfactual	Difference pre-waiver	Difference post-waiver
Pre-waiver	132,095	307,308	307,308	175,212	593,134
Post-waiver	188,466	781,601	363,678		
Difference in difference	417,922				

Table 3
Difference in difference estimation dependent variable: Monthly sales (by group) January 2018–July 2022.

	Coefficients	Adjusted R^2	F-statistic
Constant	−356,483.5 (−4.35)***		
W	175,212.3 (2.90)***		
D	16,363.74 (0.749)		
W * D	417,922.2 (5.83)***		
G	177,608.6 (6.99)***		
		0.78	86.8***
Number of observations	110		

*** Significance at the 1% level. t-ratios in parenthesis.

Our taxonomy considers four types of invention categorised according to whether they are: (1) *CPR Negative*; (2) *CPR Neutral*; (3) *CPR Positive*; or (4) *CPR Positive Plus*. In this section we discuss the policy implications of each of these 4 cases in turn.

In the case of *CPR Negative* inventions (e.g. fracking) patents may have a positive effect on CPRs as they slow down the diffusion of CPR depleting technologies. However, as the case of fracking illustrates, patents also prevent a full assessment of the impact of new technologies by restricting research and testing activities. Therefore, patent laws should be revised to permit the use of *CPR Negative* technologies for testing purposes. The case of *CPR Neutral* inventions has no implications for the protection of public health and the environment and therefore the standard trade-off between R&D incentives and diffusion is unaffected.

In the case of *CPR Positive* inventions, the use of voluntary or internationally agreed patent waivers would help resolve the patents paradox in favour of diffusion. Toyota's voluntary patent waiver helped speed diffusion and develop the EV market, reducing production costs, and arguably resulting in a gain for producers and society. Results from our econometric analysis provide support for a positive impact of the Toyota waiver and technical assistance policy. However, the waiver came around 20 years after the first (hybrid) electric vehicles entered commercial production. This suggests that relying on voluntary waivers by individual firms is unlikely to produce fast enough results given the time-critical nature of climate change. Even in cases where patent waivers benefit both patent owners and users, individual firms may be slow to find the necessary institutional arrangements, and policy makers may be slow to appreciate the scale and imminence of the threat. This mismatch between the time horizons of decision makers and the time-critical nature of environmental and public health challenges illustrates the type of biases in human decision making that policy design needs to overcome (Klenert et al., 2020).

For the last category of our taxonomy - *CPR Positive Plus Network Externalities* - there is a strong case for waiving patents, unless it can be demonstrated that there is no infringement on the public interest and that a certain level of diffusion can be achieved in a timely manner. For vaccines, the rationale springs from the fact that restricting diffusion via patents undermines vaccine efficacy, while in the case of battery electric vehicles slowing diffusion delays the co-development of charging networks thereby reducing the *use value* of electric vehicles making it harder for the technology to break through and keeping society locked into ICE vehicles. While TRIPS makes provision for compulsory licensing of technologies, at the time of writing, no low-income economy has sought to CL the production of a COVID-19 vaccine (or electric vehicles technology). This is consistent with the evidence from our pre and post TRIPS natural experiments showing that for patent policy, compulsory licensing is not sufficient for timely diffusion.

Our natural experiments indicate that for patent waivers to be effective in the case of *CPR Positive* and *CPR Positive Plus* further conditions need to be met. First, where an emergency of international concern relating to global CPRs is declared by an organisation such as the WHO or UN, a patent waiver should be automatic. The voluntary patent waiver for COVID-19 vaccines agreed in June 2022 came too late, resulting in unnecessary loss of life and economic output. Second, by itself a patent waiver is insufficient and needs to be supported by other policy measures to speed diffusion via technology transfer, innovation to meet local conditions and greater geographic spread of production capabilities. This will require building R&D and manufacturing capacity for more complex vaccines in low and middle-income countries to enable them to close the gap with wealthier economies (Smith et al., 2011). Our case study evidence on vaccines highlights the benefits of a more open system. Salk's unpatented polio vaccine in the 1950s led to the type of innovations in local vaccination administration, such as use of an oral vaccine and resolution of local production bottlenecks (Blume, 2005), that will be required for future pandemic preparedness. In the case of electric vehicles, technology and production transfer to emerging economies could be funded from the $100bn per annum pledged by developed economies to developing economies under the Paris Agreement.

A third condition concerns dual track, near and clear time-limited targets, supported by adequate funding. Under the Montréal Protocol dual track deadlines - for developed and developing economies - to cut CFC gases, supported by a multilateral fund to facilitate technology transfer including payment of patent royalties, and an effective monitoring system, illustrate how policies may be used in combination to speed transition to greener technologies. Such an international agreement via a UN Protocol to phase out ICE vehicles is an achievable aim given that the largest patent holder in the field (Toyota) has already taken the lead in this direction. If supported by effective monitoring and a multilateral fund to aid technology diffusion, this could create a *quasi* patents commons with binding commitments, coordination and funding – key ingredients that were missing from previous patents commons initiatives (Contreras et al., 2018).

Our taxonomy provides a framework for the kind of private and public institutional arrangements that may be catalysed by policy to enable the diffusion of knowledge-based capabilities (e.g. Orsatti et al., 2020; Porter and van der Linde, 1995) to resolve CPR dilemmas. This combined policy approach for *CPR Positive* and *CPR Positive Plus* categories, would favour diffusion over incentives for R&D meaning that other policies would be necessary to maintain R&D at appropriate levels. Here it is worth noting that much EV vehicle R&D was financed by the MITI in Japan. Similarly, much of the R&D for vaccines came from public sources. Other policy measures that may be used in addition to public finance include: third sector funding of R&D; patent prizes; and direct contracting of research (Wright, 1983; Dosi and Stiglitz, 2014).

In summary, maintaining recovery from the COVID-19 pandemic and enhancing preparedness for future pandemics will require innovation to deal with new variants and to develop vaccines suited to local conditions where refrigerated storage and public health systems may be an issue. A key policy message from our taxonomy and empirical

analysis in the case of vaccines for global pandemics is that IPR should be immediately waived as soon as a pandemic is announced, and knowledge and technology transfer should be supported by policy measures to strengthen innovation systems across the globe. In the case of green technologies, our findings indicate that diffusion could be speeded up by companies voluntarily waiving their patents; but faster and more efficient results would be achieved by policy measures to catalyse internationally agreed patent waivers, supported by non-patent regulations. Ultimately this will require a strengthening of international governance and institutional cooperation at a scale unseen since Bretton Woods.

Credit authorship contribution statement

Juana Bustamante: Investigation, Writing – original draft, Writing – review & editing. **Christine Oughton:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Vanesa Pesque-Cela:** Investigation, Writing – original draft, Writing – review & editing. **Damian Tobin:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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References

Ahn, J.M., Roijakkers, N., Fini, R., Mortara, L., 2019. Leveraging open innovation to improve society: past achievements and future trajectories. R&D Manag. 49 (3), 267–278.

Alawieh, A., Sabra, Z., Langley, E.F., Bizri, A.R., Hamadeh, R., Zaraket, F.A., 2017. Assessing the impact of the Lebanese National Polio Immunization Campaign using a population-based computational model. BMC Public Health 17 (1), 902. https://doi.org/10.1186/s12889-017-4909-0 (Nov 25).

Arthur, W.B., 1989. Competing Technologies, Increasing Returns, and Lock-In by Historical Events. Economic Journal 99 (394), 116–131. https://doi.org/10.2307/2234208.

Aylward, R.B., Mansour, E., Aly Don, E.S., Haridi, A., Kheir, E.I., A., and Hassan, A., 1997. The eradication of poliomyelitis in Egypt: critical factors affecting progress to date. J. Infect. Dis. 175 (Suppl), S 56–S 61.

Barton, B., Schütte, P., 2017. Electric vehicle law and policy: a comparative analysis. J. Energy Nat. Resour. Law 35 (2), 47–170.

Berman, D., 1999. AIDS, essential medicines, and compulsory licensing. J. Int. Assoc. Phys. AIDS Care 5 (4), 24–25.

Biagioli, M., 2019. Weighing intellectual property: can we balance the social costs and benefits of patenting? Hist. Sci. 57 (1), 140–163.

Blum, Nava, Katz, E., Fee, E., 2010. Natan Goldblum: the pioneer producer of the inactivated poliomyelitis vaccine in Israel. Am. J. Public Health 100, 2074–2075.

Blume, Stuart S., 2005. Lock in, the state and vaccine development: lessons from the history of the polio vaccines. Res. Policy 34 (2), 159–173.

Borrell, J.R., 2007. Pricing and patents of HIV/AIDS drugs in developing countries. Appl. Econ. 39 (4), 505–518.

Borrell, J.R., Watal, J., 2002. Impact of patents on access to HIV/AIDS Drugs in developing countries. In: CID Working Paper Series 2002.92, Harvard University, Cambridge, MA, May 2002.

Bown, C.P., Bollyky, J.P., 2021. How COVID-19 vaccine supply chains emerged in the midst of a pandemic. In: Peterson Institute for International Economics, Working Paper.

Burrone, E., Gotham, D., Gray, A., de Joncheere, K., Magrini, N., Martei, Y.M., Gore, C., Kieny, M.P., 2019. Patent pooling to increase access to essential medicines. Bull. World Health Organ. 97 (8), 575–577. https://doi.org/10.2471/BLT.18.229179 (1).

Cahoy, D., Gehman, J., Lei, Z., 2013. Fracking patents: the emergence of patents as information-containment tools in shale drilling. Mich. Telecommun. Technol. Law Rev. 19, 279–330.

Campi, M., Nuvolari, A., 2015. Intellectual property protection in plant varieties: a worldwide index (1961-2011). Res. Policy 44 (4), 951–964.

Web of Science Core Collection Database, Clarivate.

Clugston, C., 2021. The infamous failure of the eco-patent commons and the quiet success of the WIPO Green Project: what we can learn about disseminating green tech to developing countries. Vermont J. Environ. Law Ecoperspectives Blog 20 May. Available at: https://vjel.vermontlaw.edu/.

Contreras, J.L., 2012. Standards, patents, and the National Smart Grid. Pace Law Rev. 32, 641–675.

Contreras, J.L., Hall, B.H., Helmers, C., 2018. Green Technology Diffusion: A PostMortem Analysis of the Eco-patent Commons (No. w25271). National Bureau of Economic Research.

Davies, M., 2022. WHO efforts to bring vaccine manufacturing to Africa are undermined by the drug industry. Br. Med. J. 376, o304 https://doi.org/10.1136/bmj.o304.

Davies, A.M., Marberg, K., Goldblum, N., Levine, S., Yekutiel, P., 1960. Epidemiology of poliomyelitis in Israel 1952-1959, with evaluation of Salk vaccination during a three-year period. Bull. World Health Organ. 23, 53-7221-12.

De Sombre, E.R., 2000. The experience of the Montreal Protocol: particularly remarkable and remarkably particular. J. Environ. Law 19 (49), 49–81.

Dosi, G., Stiglitz, J., 2014. The role of intellectual property rights in the development process, with some lessons from developed countries: an introduction. In: Cimoli, M., Dosi, G., Maskus, K., Okediji, R. (Eds.), Intellectual Property Rights: Legal and Economic Challenges for Development. Oxford University Press, Oxford.

Dosi, G., Marengo, L., Pasquali, C., 2006. How much should society fuel the greed of innovators? On the relations between appropriability, opportunities and rates of innovation. Res. Policy 35, 1110–1121.

Duke Global Health Innovation Centre, 2020. Press release on Covid-10 vaccine advance market commitments, launch and scale speedometer, 2 November 2020. accessed at. https://dukeghic.org/wp-content/uploads/sites/20/2020/11/COVID-19-Vax-PressRelease_28Oct2020-1.pdf.

Financial Times, 2019. Carmakers' designs on patents for the future, 9 July 2019, Financial Times. https://www.ft.com/content/8a9613c4-8ac3-11e9-b8cb-26a9caa9d67b.

Frederico, P.J., 1936. Operation of the Patent Act of 1790. J. Patent Office XVIII (April), 237–251.

Goldblum, N., Gerichter, C.B., Tulchinsky, T.H., Melnick, J.L., 1994. Poliomyelitis control in Israel, the West Bank and Gaza Strip: changing strategies with the goal of eradication in an endemic area. Bull. World Health Organ. 72 (5), 783–796.

Hardin, G., 1968. The tragedy of the commons. Science 162 (3859), 1243–1248.

Heller, M.A., Eisenberg, R.S., 1998. Can patents deter innovation? The Anticommons in biomedical research. Science 280 (5364), 698–701.

Helpman, E., 1993. Innovation, imitation, and intellectual property rights. Econometrica 61 (6), 1247–1280.

Huber, N., 2022. Nations Urged to Waive IP on Vaccines as Drugmakers Argue Current Rules Are Fair. Financial Times (June 16).

International Energy Agency (IEA), 2020. Global EV Outlook 2020. IEA, Paris.

John Hopkins Corona Virus Resources Centre, 2020. Economics of Covid-19 vaccines, vaccine reports. accessed at. https://coronavirus.jhu.edu/vaccines/report/economicsof-covid-19-vaccines.

Kapp, K.W., 1963. The Social Costs of Business Enterprise. Spokesman Press, Nottingham.

Klenert, D., Funke, F., Mattauch, L., O'Callaghan, B., 2020. Five lessons from COVID-19 for advancing climate change mitigation. Environ. Resour. Econ. 76, 751–778.

Lancet Commission, 2022. The *Lancet* Commission on lessons for the future from the COVID-19 pandemic. Lancet. https://doi.org/10.1016/S0140-6736(22)01585-9 (Published Online: September 14, 2022).

Langreth, R., Decker, S., 2020. Moderna Won't Enforce Covid Vaccine Patents During Pandemic. Bloomberg (October 8).

Lee, A., 1989. Case studies as natural experiments. Hum. Relat. 42 (2), 117–137.

Levin, R., Klevorick, A., Nelson, R., Winter, S., 1987. Appropriating the returns from industrial research and development. Brook. Pap. Econ. Act. 783.

Love, J., 2001. Access to medicine and compliance with the WTO TRIPS Accord, United Nations Development Programme Consumer Project on Technology. http://www.cptech.org (2001).

Machlup, F., 1958. An Economic Review of the Patent System Discussion Paper, U.S. Congress, Washington, DC. Government Printing Office.

Machlup, F., Penrose, E., 1950. The patent controversy in the nineteenth century. J. Econ. Hist. 10 (1), 1–29.

Mauler, L., Diffner, F., Leker, J., 2021. Economies of scale in battery cell manufacturing: the impact of material and process innovations. Appl. Energy 286, 1–14.

McAdams, D., McDade, K.K., Ogbuoji, O., Johnson, M., Dixit, S., Yamey, G., 2020. Incentivising wealthy nations to participate in the COVID-19 Vaccine Global Access Facility (COVAX): a game theory perspective. BMJ Glob. Health 5, 1–7.

Mendez, R., 2021. Africa suffers worst surge in Covid cases as delta variant spurs third wave of pandemic. July 8. Available at, CNBC. https://www.cnbc.com/2021/07/08/delta-variant-africa-suffers-worst-surge-in-covid-cases-officials-brace-for-third-wave.html.

Moore, C., 1990. Industry responses to the Montreal Protocol. Ambio 19 (6/7), 320–323.
Moser, P., 2013. Patents and innovation: evidence from economic history. J. Econ. Perspect. 27 (1), 23–44.
Nelson, R.R., 2006. Reflections of David Teece's "Profiting from technological innovation…". Res. Policy 35 (8), 1107–1109.
Ochmann, S., Roser, M., 2017. Polio. Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/polio.
Orsatti, G., Quatraro, F., Pezzoni, M., 2020. The antecedents of green technologies: the role of team-level recombinant capabilities. Res. Policy 49 (3), 1–17. https://doi.org/10.1016/j.respol.2019.103919.
Ostrom, E., 1990. Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge University Press, Cambridge.
Ostrom, E., 2008. The Challenge of Common Pool Resources. Environment: Science and Policy for Sustainable Development, July/August, pp. 1–10.
Ostrom, E., Gardner, R., Walker, J., 1994. Rules, Games and Common-pool Resources. University of Michigan Press, USA.
Oxfam, 2022. WTO agrees a deal on patent for COVID vaccines – but campaigners say this is absolutely not the broad IPR waiver the world desperately needs. Press Release. https://www.oxfam.org/en/press-releases/wto-agrees-deal-patents-covid-vaccines-campaigners-say-absolutely-not-broad.
Pistor, K., 2019. The Code of Capital. Princeton University Press, Princeton, N.J.
Polanyi, K., 1944. The Great Transformation: The Political and Economic Origins of Our Time. Beacon Press, Massachusetts.
Porter, M., van der Linde, C., 1995. Toward a new conception of the environment-competitiveness relationship. J. Econ. Perspect. 9 (4), 97–118.
Robinson, J., 1956. The Accumulation of Capital. Cambridge University Press, Cambridge.
Roelf, W., Steenhuysen, J., 2022. Charities Say Moderna Patents Could Hit Africa Covid Vaccine Hub. Reuters (February 17).
Roser, M., Ritchie, H., Ortiz-Ospina, E., Hasell, J., 2022. Coronavirus Pandemic (COVID-19) Dataset. Our World in Data.
Schiff, E., 1971. Industrialisation Without Patents: The Netherlands, 1869-1912; Switzerland, 1850-1907. Princeton University Press, Princeton, NJ.
Shadlen, K.C., Sampat, B.N., Kapczynski, A., 2020. Patents, trade and medicines: past, present and future. Rev. Int. Polit. Econ. 27 (1), 75–97.
Smith, J., Lipsitch, M., Almond, J.W., 2011. Vaccine production, distribution, access, and uptake. Lancet 378 (9789), 428–438.
Son, K.-B., 2019. Importance of the intellectual property system in attempting compulsory licensing of pharmaceuticals: a cross-sectional analysis. Glob. Health 15 (42), 1–48.
Sparke, M., 2020. Neoliberal regime change and the remaking of global health: from rollback disinvestment to rollout reinvestment and reterritorialization. Rev. Int. Polit. Econ. 27 (1), 48–74. https://doi.org/10.1080/09692290.2019.1624382.
Stavropoulou, C., Valletti, T., 2015. Compulsory licensing and access to drugs. Eur. J. Health Econ. 16 (1), 83–94.
Swartz, T.A., 2008. The epidemiology of polio in Israel an historical perspective. In: Israel Center for Disease Control (ICDC), Ministry of Health, Publication No. 317.
Teece, D., 1986. Profiting from technological innovation: implications for integration, collaboration, licensing and public policy. Res. Policy 15, 285–305.
The Economist, 2021. Third time unlucky. De Economist 440 (9252) (July 3).
Torrisi, S., Gambardella, A., Giuri, P., Harhoff, D., Hoisl, K., Mariani, M., 2016. Used, blocking and sleeping patents: empirical evidence from a large-scale inventor survey. Res. Policy 45 (7), 1374–1385.
Toyota, 2019. Why is Toyota giving away its vehicle electrification patents? Joe Clifford, Toyota UK Magazine. https://mag.toyota.co.uk/toyota-vehicle-electrification-patents/.
UNAIDS, 2021. Global HIV and AIDS statistics – fact sheet. Available at: https://www.unaids.org/en/resources/fact-sheet.
UNEP, 2016. Briefing note on intellectual property rights and the Montreal Protocol: past practices and current challenges. In: UNEP Ozone Secretariat, 375th OWEG, Geneva, Switzerland, 4-8th April accessed at: https://ozone.unep.org/resources?q=resources&page=7. accessed at:
UNEP, 2021. UN Environment Programme: the Montreal Protocol. accessed at: https://www.unep.org/ozonaction/who-we-are/about-montreal-protocol.
UNEP Ozone Secretariat, 2021. Data. Available at: https://ozone.unep.org/countries/datatable.
Urias, E., Ramani, S.V., 2020. Access to medicines after TRIPS: is compulsory licensing an effective mechanism to lower drug prices? A review of the existing evidence. J. Int. Bus. Policy 3 (4), 367–384.
US Public Health Reports, 1967. Surveillance of poliomyelitis in the United States, 1962-65. Vol. 82 (5), 417–428.
Walker, L., 2022. South Africa 'Cracks Code' of Covid Vaccine, Working on Patent-free Version. The Brussels Times (February 2).
Watson, O., Barnsley, G., Toor, J., Hogan, A., Winskill, P., Ghani, A., 2022. Global impact of the first year of COVID-19 vaccination: a mathematical modelling study. Lancet 22 (September), 1293–2022.
WHO, 2020. Global Vaccine Market Report World Health Organisation, Working Draft, pp. 1–12 (December 2020).
WHO, 2021. WHO supporting South African consortium to establish first Covid mRNA vaccine technology transfer hub. June 21. Available at: https://www.who.int/news/item/21-06-2021-who-supporting-south-african-consortium-to-establish-first-covid-mrna-vaccine-technology-transfer-hub. (Accessed 1 August 2022).
WHO Africa, 2022. What is Africa's vaccine production capacity? Available at: https://www.afro.who.int/news/what-africas-vaccine-production-capacity. (Accessed 1 August 2022) (March 19).
World Development Indicators, 2022. Available at: https://databank.worldbank.org/source/world-development-indicators.
Wright, B., 1983. The economics of invention incentives: patents, prizes, and research contracts. Am. Econ. Rev. 73 (4), 691–707 (Sep., 1983).
Ziegler, M.S., Trancik, J.E., 2021. Re-examining rates of lithium-ion battery technology improvement and cost decline. Energy Environ. Sci. 14, 1635–1651.
Ziegler, M.S., Trancik, J.E., 2021b. Data Series for Lithium-ion Battery Technologies. https://doi.org/10.7910/DVN/9FEJ7C (Trancik Lab Dataverse, V1, UNF:6:sVT2vBwWolbQL4BxsTSDUg== [fileUNF]).