Resolving the Patents Paradox in the Era of Covid19 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 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 amongst 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, such as public health and the environment. This class includes vaccines and inventions that reduce externalities, such as, CFC gases and greenhouse gas emissions. In these instances, the effectiveness of inventions depends critically on rapid global diffusion. Our theoretical analysis utilises a game-theoretic approach to analyse the complexities surrounding inventions for the protection of CPRs. We find that the effectiveness of inventions to protect CPRs depends on the contextual and 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 that takes account of the anomalies raised by CPRs. For CPR inventions 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.

JEL Codes: O3 Innovation, R&D, Technological Change, Intellectual Property Rights; I1 Health; I18 Public Health; Q5 Environmental Economics; Q55 Technological Innovation; Q58 Government Policy

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> *"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).

> "*To say that patents are effective incentives of economic activity is one thing; it is quite another to contend that they are necessary for inducing an adequate amount of such activity*." Machlup and Penrose (1950).

> "*the principles of business enterprise favor the emergence of the social costs of air pollution." … "Industry does not spend considerable sums on research dealing with the prevention of social costs".* Kapp (1963).

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 the role of IPR 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 patent laws. IPRs have also been applied differently with some laws specifying assessment of applications on a case-by-case review of potential costs and benefits, to the current system where assessment is made primarily on the basis of originality and property rights (Biagioli, 2019). 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. A further and related question is whether patents are the best way to incentivise investment in R&D. 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, Covid19 and the climate crisis have accentuated those anomalies and put them under the spotlight of widespread public debate.

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 IPR. 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 externalities; and (iii) the wider regulatory environment within the context of regional, national and global innovation systems. To that end we set out a taxonomy of patents/inventions that includes the case of patenting of technologies designed to preserve or enhance CPRs, such as public health and the environment, as these are critical in the current era of Covid19 and climate change.

CPRs are non-excludable and subtractable making them subject to the tragedy of the commons hallmarked by a conflict between individual (private) and collective (public) interests. Inventions and patents for CPRs include vaccines and technologies that reduce externalities, such as greenhouse gas emissions. We argue that in the case of CPRs, the *efficacy* of inventions is not independent of the speed and extent of diffusion, indeed the effectiveness of vaccines and zero-carbon technologies depends critically on rapid, global 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 Covid19 and climate change. Section 3 provides a conceptual framework for our analysis setting out a taxonomy of cases to inform the design of policies to promote R&D and diffusion. Within this taxonomy we focus on the complex case of inventions to protect CPRs, such as vaccines and low/zero-carbon technologies designed to protect public health and the environment, using a game-theoretic framework. 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 Covid19 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 Montreal Protocol, and current 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 more flexible policy: the Nationally Determined

Contributions of the Paris Agreement. Section 5 discusses the policy implications of our theoretical and empirical analysis for the system of IPR and the creation and diffusion of inventions/innovations to protect CPRs. Section 6 concludes by considering the broader implications of our findings for international governance of IPR and CPRs and highlights areas for future research, in particular, how science and social science could be used in partnership to mitigate the effects of global challenges such Covid19 and climate change, whilst also promoting catch up and economic equality across regions.

2. Patents Pre and Post-TRIPS: A Review of the Literature

2.1 Patent system prior to TRIPS – limited evidence of effectiveness in promoting innovation

Understanding how the aspects of the patent system that are ill-equipped to deal with complex global challenges can be improved upon, requires an appreciation of the contested origins of the contemporary patent system prior to TRIPS and the scale of the challenge now facing 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 the social loss is already apparent in such CPRs as public health and the environment where much of the technology for sustainable development already exists (Clugston, 2021); what is missing is an appropriate mechanism to support its rapid diffusion. Widely available vaccines have been key to combating the spread of viruses such as polio (Blume, 2005). But vaccine research networks have become privatised and fragmented, while vaccines for a wide range of diseases are now in short supply (WHO 2020). Electric vehicles offer a solution for stemming the rise of harmful emissions. Although their sales have soared over the last decade, only a handful of countries have achieved a market share of greater than 1 per cent. In 2010, only five countries had more than 1,000 electric cars on their roads: China, Japan, Norway, the US and UK (IEA, 2020: 39). By 2019 only five countries (Norway (13%), Iceland (4.4%), Netherlands (2.7%), Sweden (2.0%) and China (1.6%)), had a share that exceeded 1.5 per cent (IEA, 2020: 44).

A Lack of Consensus

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 invention. 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). Objections to the patent system 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). Historical evidence supports these objections. 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 innovations 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).

Against these objections, 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, 1997; 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 licences becomes so high as to make production uneconomical (Contreras, 2012).

The effect of national pharmaceutical patent legislation on domestic innovation shows a close association between patent protection and other measures of economic development including the level of R&D activity, the overall market environment, and international integration (Ginarte and Park, 1997). Qian's (2007) study on 26 countries for the period 1978-2002 indicates that national patent protection is not sufficient to stimulate innovation but finds evidence of accelerated innovation in countries with higher levels of economic development, educational attainment and economic freedom.

Patent Stacking and the Problem of the Anti-Commons

Common-pool resources, such as public health and the environment 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. This is the mirror opposite of the tragedy of the commons, where instead of a CPR suffering from overuse, a privatised resource suffers from underuse (Heller and Eisenberg (1998). Looking at the case of biomedical research, Heller and Eisenberg (1998) show how the patent system created too many concurrent fragments and incentivised the stacking of licenses producing an anti-commons. These practices impede progress and diffusion by creating too many concurrent fragments of intellectual property rights 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 intellectual property rights deter researchers from pursuing innovative research in these areas.

Fragmentation in Vaccine Production

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 and other technologies. Vaccines are not 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) reports that 56 out of 132 reporting countries (42%) reported national stockouts of one or more vaccines and 34 countries reported stockouts of two or more including oral polio and yellow fever 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 are now more concentrated with four firms (GSK, Pfizer, Merck, and Sanofi) controlling 90% of global market value and five produce 60 percent of global volume (SII, GSK, Sanofi, BBIL and Haffkine) (WHO, 2020: 4). Within these firms the production of vaccines has become 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 vaccines faces significant barriers in terms of the stacking of licenses.

2.2 The Patent System, TRIPS and Low-Income Economies

The social loss from restricting knowledge is especially severe in low-income economies. The application of patents has become more complex, extending intellectual property rights to trade agreements involving a variety of products from agricultural products to advanced technologies and pharmaceuticals (Love, 2001; Shadlen et al 2020; Camp and Nuvolari, 2015). Yet the benefits of this for low-income economies are far from clear. Efforts to model the welfare impacts of tighter intellectual property regimes on innovation in developed economies and imitation in less developed economies indicate that the initial acceleration of innovation in developed economies would be insufficient to compensate less developed economies for its subsequent decline (Helpman, 1993).

Since the Uruguay round of the World Trade Organisation (WTO) negotiations (1986-94), all WTO members became party to the Trade-Related Aspects of Intellectual Property Rights (TRIPs) Agreement. These agreements integrated intellectual property 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). Although the WTO Doha Declaration reinstated the right of states to use compulsory licensing in times of public health emergencies, these agreements still offered 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 (Sparkle, 2020). A lack of production capabilities remains a key obstacle for developing economies in accessing more advanced vaccines (Smith et al, 2011).

Mapping and Diffusing Capabilities

The above discussion reflects the fact that in resolving grand challenges that require a 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). Part of the reason for this is that much of the innovation that is beneficial to society can occur outside of the patent system in societies where the patent system is not strong, and innovation is not captured in official patent data (Moser, 2013). In lower income economies such activities are often incorrectly labelled as imitation, when in fact they are crucial to the development of adsorptive capacity (Helpman, 1993). Secondly, firm specific capabilities especially in many CPRs tends to be unequally distributed. In mapping vaccine production capabilities, Bown and Bollyky (2021) show that the capabilities for vaccine manufacturing are mostly located in the US and Europe, with small presence in Japan and China.

Alternatives: Compulsory Licencing, Prizes, Pools and Pledges

In highlighting the anomalies of the patent system, the above discussion indicates that 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, patents and offshoots of the patent system such as compulsory licencing are unlikely to help all that much. Instead, alternatives to the patent system must be assessed in terms of their potential to induce the transfer of technologies and capabilities for production to lower income countries.

One of the main policy tools available to governments to deal with anomalies in the patent system is compulsory licensing. Compulsory licenses 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 compulsory licensing by low and middle-income countries has been sporadic (Son, 2019). 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). Although compulsory licensing has been used as a way of addressing shortage, Son (2019) finds that countries with more developed patent systems are more likely to use compulsory licensing. The rationale underpinning this is that a compulsory license requires a functioning patent system.

Prizes and other administratively coordinated awards offer a non-market alternative to patents and have offered a rich source of historical examples (Moser, 2013). One option is to reward patentees at "a level ample enough to give general satisfaction to inventors and their financial position" (Polanyi, 1944: 67). The costs of this approach would be offset by the public benefits of quicker technological progress. Theoretical models indicate that the range of situations where the patents dominate other mechanisms is overvalued while the situations where prizes and other mechanisms dominate is undervalued, suggesting value in further exploring the role of prizes (Wright, 1983). Yet, despite their historical popularity in the US and Europe, the evidence on the role of prizes is mixed. A particular deficiency of prizes that is directly relevant to the case of CPRs relates to their governance and the industrial and technical capabilities needed for their effective and impartial administration (Khan, 2015). In these instances, the market orientation of the patent system often proved more attractive.

Alternatives that address some of the anomalies in the patent system regarding common pool resources, especially the problem of stacking and the anti-commons, 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. Pledges differ from patent pools and cross licensing by conferring benefits on 3rd 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). A study examining the Eco-Patent Commons, an innovative not-for-profit initiative with the objective of pledging green technology patents royalty free to accelerate their adoption by Contreras et al (2018), shows that the patents contributed did not attract a lot of interest even before contribution and pledging to the commons did not increase interest or promote diffusion. Their findings highlight that patent disclosure alone is not sufficient for uptake without a dedicated coordination system to provide dedicated administrative support and managerial resources to promote the commons.

3. A Patents Taxonomy from Essential Goods to Common Pool Resources

The preceding discussion has highlighted the role of context specific variables in shaping R&D and innovation. We build on the existing literature to specify a taxonomy of patents based on classes of characteristics covering the nature of the industry, externalities and the wider innovation system(s) and regulatory environment. As we have seen, the theoretical and empirical evidence on the effects of patents is mixed, while policy has come down firmly in favour of prioritising incentives for R&D rather than favouring diffusion.

Biagioli (2019) has questioned the idea that it is possible to weigh the costs and benefits of current patent law using empirical evidence since costs and benefits are measured differently and cannot be meaningfully weighed against each other. He concludes that if we cannot be sure that the patent system as a whole is beneficial then an alternative to advocating abolishment would be to look in more detail at the merits and demerits of patents on a case-by-case basis, as initially envisaged in the US Patent Act 1790. However, as Biagioli notes, this became unworkable because of the time taken to review the pros and cons of individual applications and the appraisal process was subsequently watered down to issues around originality and infringements of IPR rather than impact. Biagioli (2019) advocates a more industry-specific approach that assesses the pros and cons of patents in a local context. Building on the idea of a need for a more nuanced approach we set out a taxonomy of patents which enables us to identify cases where greater consideration of the costs and benefits would be beneficial.

Table 1 specifies a patents taxonomy based on 6 classes and summarises the costs, benefits and efficacy of each class by type of product and invention/technology, taking account of industry characteristics and externalities. We start in Row 1, Class 1 with Non-Essential Goods with competitive markets and substitute goods. The standard appraisal of costs and benefits applies to this type of industry and the use of a patent does not affect the efficacy of the product. Moving on to the Class of Patents for Essential Goods in Row 2 the picture changes somewhat, especially in the case of goods, such as mains water supply that are natural monopolies. Here, the patent over a particular quality-improving technology is likely to increase the price of an essential commodity (Allan, 2014). Of course, natural monopolies are often regulated, or licensed as state owned corporations, so the full cost of the patent may not be passed onto consumers. It could fall on the state or on the profits of a regulated, private water company, which shows that patent law has to be seen in the context of the wider legal framework, such as laws regulating natural monopolies. The picture becomes more complex for the Class of Goods with Significant Economies of Scale in Row 3. Reaching minimum efficient scale (MES) of production may require high levels of output before a new product can attain an equal footing with existing products that are already produced at scale.[5] The higher prices and lower output occasioned by patents may therefore make it difficult for new technologies to break through. As Whitmarsh et al (2008) show in the case of hybrid vehicle technology, it needed the environmentally friendly regulatory framework in California to create sufficient market demand for Toyota and Honda's hybrid vehicles to gain traction. Again, this shows that the impact of patents is dependent on the characteristics of the industry, the regulatory environment and the potential to reduce negative externalities. Row 4 considers the Class of Patents for Goods with Positive Externalities, such as pharmaceutical drugs. In this case the ability to cure

[5] These are more easily realised within large markets, for example, the size of the US market is often cited as a factor underlying its economic leadership and productivity.

Table 1 Taxonomy of Patents: Costs, Benefits and Efficacy

Kind of Product	Invention/ Technology	Benefits	Costs	Does patent-slowed diffusion reduce the efficacy of the invention/technology?	Are patents best tool to induce R&D
1. Non-Essential Goods	Turntable, Food Mixer,	• Higher profit to owner • Spread of codified knowledge	• Higher price • Lower output and slower diffusion • Buyers can switch to other products	No	?
2. Essential Goods (e.g. Water)	Water purification technology	• Higher profit to owner • Spread of codified knowledge	• Higher price/lower output (regulation may limit price increases) • Slower diffusion	No	?
3. Goods with Significant Economies of Scale	Hybrid Cars	• Higher profit to owner • Spread of codified knowledge • Lower emissions	• Higher prices/lower output • Slower diffusion • Restricted output/demand implies unit costs likely to be above MES level, which also slows diffusion	No	?
4. Goods with positive externalities	Pharmaceutical drugs	• Higher profit to owner • Spread of codified knowledge • increased life expectancy and well-being	• Higher prices • Reduces public health budgets available for other treatments • Some patients not treated • Slower diffusion	No	?
5. Goods with Network Externalities	Charging points for electric vehicles	• Higher profit to owner • Spread of codified knowledge • Lower emissions	• Higher prices • Lower output and slower diffusion imply network externalities and emissions are not optimal	Yes	?/No
6. Common Pool Resources (e.g. Public Health and the Environment)	Vaccines, Low/Zero Carbon Technologies	• Higher profit to owner • Spread of codified knowledge • Increased life expectancy and well-being	• Higher prices • Lower output and slower diffusion • Slower diffusion undermines efficacy of vaccines and low/zero carbon technologies	Yes	No

diseases has many positive effects including increasing life expectancy, reducing the time patients take off work and the time spent in hospital, thus freeing up scarce health care services.

Patent Class 5 covers Goods with Network Externalities, where the utility of using a good depends on the number of goods in use. Examples of such goods include mobile phones, computer software systems and electric vehicle charging points (EVCP). If we consider the case of EVCP, the value of owning an electric vehicle increases with the size of the EVCP network. Hence, there is a negative externality from patents on EVCP that impacts the development of the EV industry. Slowing down the development of the EVCP network by making it more expensive reduces its value to users and further slows down diffusion. Lock-in to existing technologies is one of the factors that has made it difficult for EVs to gain market share over conventional combustion engines. Realising the benefits from EV technology requires coordination and a large number of consumers and supplies to switch together. Without a strong coordinating mechanism, such as regulation of vehicle emission standards, switching to a more efficient technology with lower externalities may be slow and difficult. As a result, negative externalities will persist and may outweigh the positive benefit to patent holders of higher prices, in addition to the effect of higher prices.

Finally, in Row 6 we come to the Class of Patents for CPRs, such as public health and the environment. CPRs are substractable and not easily excludable meaning that the more one agent uses, the less is available for others and the ability to prevent over-use is limited. Classic examples of CPRs include common pasture lands and fish stocks; more current examples include public health and the environment. CPRs are subject to the tragedy of the commons characterised by a conflict between the individual and common interest. In the case of public health, areas free from viral infection represent a CPR that may be ruined by those carrying a viral infection. Vaccinations can provide significant positive externalities beyond the individual protection afforded to the user (Gaudin, 2019) thus protecting the common pool resource. In the case of the environment, the atmosphere is a common pool resource that may be destroyed by CO_2 emissions. Vaccines and low emissions vehicles designed to protect public health and the environment in the case of a pandemic and climate change, respectively, can only do so if they are diffused rapidly and globally. For this class of inventions and associated innovations, patents are counterproductive because slowing diffusion undermines the very efficacy of the innovation. The impact of slow diffusion can be significant because the resources they protect are global and time sensitive in the sense that the efficacy of vaccines and green technologies are time critical due to cumulative effects and tipping points (Lenton et al, 2019/20). For this class of patents, there is no theoretical case for patents - which favour R&D incentives over diffusion - as the benefits are only realised via rapid and comprehensive diffusion. For CPR inventions and technologies, the scales are tipped firmly in favour of the benefits of diffusion over incentives for R&D and patent law, as it stands, is counterproductive. Of course, TRIPS does allow for the possibility of compulsory licensing which we consider in our case study of HIV/AIDS drugs.

Our taxonomy of patent classes has implications for policy. The central lesson is that the costs and benefits of patents are context specific which reinforces the point made by Cimoli, *et al* (2014:9-10) that patent and IPR policy must be viewed within the wider context of innovation systems and the regulatory environment. This does not mean that patents should be considered on a case-by-case basis but it does imply the need for a more nuanced approach to patent law. In the case of patents for technologies used to protect Classes 3, 4 and 5 of our taxonomy, account needs to be taken of the costs and benefits arising from externalities. In the case of Class 6 – patents for technologies that protect CPRs – patent law needs to be reformed to include automatic triggers (e.g. a pandemic or a climate tipping point) for patent waivers. While this is a necessary condition, it is not sufficient. Global crises, such as the Covid19 will also only be resolved by measures that support the diffusion of technological capabilities, not least because the efficacy of the product (vaccine) is dependent on the speed and extent of diffusion.

3.1 Technology, coordination and diffusion: insights from game theory in the Case of Patent Classes 3, 4, 5 and 6: Economies of Scale, Positive Externalities, Network Externalities and CPRs

In the following discussion we use game theory to explore some of the anomalies of patent classes characterised by one or more of the following features: economies of scale, network externalities, positive externalities and common pool resources.

3.2 Game Theoretic Insights in the Case of Patent Class 6: CPRs

The situation regarding Covid19 vaccinations can be modelled using game theory. The game is played between countries, as most vaccines have been bought by national governments under bi-lateral Advanced Purchase Agreements (APA) with pharmaceutical companies (McAdam, 2020; Duke Global Health Innovation Center, 2020, John Hopkins Corona Virus Resources Centre, 2020). Alternatively countries have the choice to participate in multilateral purchase schemes that share vaccines equally. The advantage of such a strategy is that it encourages widespread diffusion, prevents vaccine hoarding and avoids a situation where a rich country pre-orders many times the amount of vaccine it requires, thereby limiting the supply to poorer countries. Figure 2 sets out the payoffs in the two country case which can be extended to the *n* country case without loss of generality (Friedman, 1985). Assuming common knowledge rationality, each country chooses the bi-lateral strategy, and the Nash equilibrium outcome is [1, 1]. The outcome is Pareto suboptimal compared to the cooperative solution [2, 2], which can be achieved by changing the game from a non-cooperative to a cooperative game by, for example, the use of institutional arrangements (Ostrom, 1990, Ostrom *et al*, 1994).

Figure 2 Vaccination Game

		Country 2	
		Bilateral APA Individual Strategy	Multilateral APA Cooperative Strategy
Country 1	Bilateral APA Individual Strategy	[1, 1]	[5, 0]
	Multilateral APA Cooperative Strategy	[0, 5]	[2, 2]

In the case of Covid19 a number of arrangements have been put in place and some of these have been agreed at international level e.g. COVAX whereby national governments can agree to purchase and donate to COVAX to share vaccines internationally with low to middle-income countries. However, countries may renege on agreements, and surplus vaccines may go out of date, so significant coordination is required to make this solution work. More significantly, there is limited supply. COVAX could be strengthened or there could be a patent waiver, but without expansion of manufacturing capacity to middle and low-income countries, the vaccination roll out has been estimated to take *at least* 2 years and there is a risk of the virus mutating amongst the unvaccinated population.

Figure 3 depicts the situation with capacity building for vaccine manufacture in middle and low-income countries, which increases the speed of diffusion and reduces the costs of lockdowns and Covid related falls in GDP, resulting in higher returns from vaccine cooperation [4, 4].

Figure 3 Vaccination Game with Patent Waiver and Technological Capacity Building

		Country 2	
		Bilateral APA Individual Strategy	Multilateral APA Cooperative Strategy with Capacity Building
Country 1	Bilateral APA Individual Strategy	[1, 1]	[5, 0]
	Multilateral APA Cooperative Strategy with Capacity Building	[0, 5]	[4, 4]

3.3 Green Technologies: Petrol Hybrid, Plug-in Hybrid and Electric Vehicles

Over 40% of carbon emissions come from transport, so the introduction of green technologies in the vehicles sector can do much to protect common pool resources. However the vehicles sector is subject to high economies of scale making it hard for new technologies to break through. And, in the case of electric (as opposed to hybrid vehicles) the sector is also locked into networks of petrol stations and the absence of comprehensive networks of charging points. These two features mean that there are likely to be coordination failures. To explore these we model the situation facing car producers as a non-cooperative game. Each producer has a choice between two strategies to switch production to low/zero emission vehicles or to continue to produce petrol and diesel vehicles. The unit cost of petrol and diesel vehicles is lower than the unit cost of low/zero emission vehicles because the market for the latter is smaller and economies of scale are not fully realised. Moreover, there is lock-in caused by well-established networks of fuel stations and limited/patchy networks of charging points. The switch to low/zero emission vehicles would be more profitable for producers if they *all* switched together creating a larger market for fuel efficient cars resulting in lower unit costs as full economies of scale are realised for the new superior technology. However, without a coordinating mechanism (regulation) any firm that switches first will lose out as the price of low/zero emission cars is higher than the price of conventional petrol/diesel cars. The strategy choices and payoffs (profits) facing firms are represented in Figure 4 for the two-player game. The game can be extended without loss of generality to the n-player case (Friedman, 1985). Assuming common knowledge rationality, the Nash equilibrium is [1, 1], which is Pareto suboptimal. Both firms could be better off by switching together to the green technology with an outcome of [3, 3]. However, this strategy is ruled out by the existence of a dominant strategy and the inability of rational players to credibly commit to switch to low/zero carbon technology. Regulation in the form of a legally required emissions standard for vehicles acts as a coordinating device to shift the outcome to [3, 3]. The coordinating effect of environmental regulation is similar to the Porter (1991) hypothesis, though in Porter's analysis regulation acts as a spur to innovation while in the case of low and zero-emissions vehicles the technology already exists and the regulatory standard acts as a switching or diffusion mechanism. Those manufacturers who have access to green technologies will benefit from fully switching their production to low emissions. Those who do not have their own patents will have to pay license fees. In both cases the standard would likely stimulate innovation around low/zero emissions technologies. Most standards are supported by other policy instruments such as funding for technological development (for example, the Montreal Protocol set targets for the reduction and elimination of CFC gases supported by US$3.9bn of funding (UNEP, 2021)). Other policy instruments can also have a positive effect, for example, pooling patents as part of the regulatory framework. In the case of pooling green technologies competition between firms will then focus, as it has tended to do anyway on design and other aspects of quality.

Figure 4 Switching to Low/Zero Emissions Vehicles Production

		Firm 2	
		Continue with High Emissions technology	Switch to Low/Zero Emissions Technology
Firm 1	Continue with High Emissions Technology	[1, 1]	[5, 0]
	Switch to Low/Zero Emissions Technology	[0, 5]	[3, 3]

Summary of Insights from Game Theory

Game theory provides a useful analytical tool for CPRs which are subject to the tragedy of the commons. It highlights the fact that left to their own devices and acting in their own self-interest, governments and businesses face incentive structures that lead to suboptimal outcomes for players and society. Our analysis also illustrates that escaping the tragedy of the commons can be achieved in various ways, including by changing the payoffs that players face, by changing the nature of the game from non-cooperative to cooperative via the use of (international) agreements between players, and by setting regulatory standards that rule out inefficient outcomes, for example, by legislating for a compulsory shift to ZEV by a fixed date.

The foregoing analysis provides the conceptual framework for our cases that have been selected to embody natural experiments by controlling for different patent and regulatory regimes. The case studies enable us to analyse the development of inventions to protect CPRs in the case of public health and the environment. Our first natural experiment focuses on the case of vaccine development with patents (Covid19) and without patents (Polio), as well as the intermediate case of the use of "patents *plus* compulsory licensing" in the case of HIV/AIDS drugs. The second natural experiment focuses on environmental technologies and compares the cases of the development of new products and processes for the elimination of CFC gases under the Montreal Protocol ratified by all 182 UN member states in 1987, and the reduction/elimination of CO_2 vehicle emissions under TRIPS and the Paris Agreement on low/zero emissions vehicles, as well as the California Air Resources Board's Zero Emissions Vehicle (ZEV) policy.

4. Case Study Evidence from Two Natural Experiments

Drawing on the above insights we examine pairs of case studies of technologies/inventions 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 (Covid19)

An important case of technology diffusion prior to TRIPS is provided by the roll out of Jonas Salk's unpatented polio vaccine. The case illustrates the importance of cooperative 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 needs and epidemiological profiles changed (Blume, 2005). The case has particular 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 leading to the launch of the Global Polio Eradication Initiative (Ochmann and

Roser, 2017).[6] Central to the eradication of polio and dealing with emerging variants has been the ability to adapt and modify vaccine production and administration in affected areas (Goldblum et al, 1994).

Following a large outbreak of polio in the mid-1950s the Israeli government decided to scale 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). On his return to Israel Goldblum implemented and adhered to the requirements of vaccine development enumerated by the United States Public Health Service. 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. This saw the number of poliomyelitis cases in Israel drop from an annual average of 650 in the years 1952 to 1956 to just 57 in 1957 after the vaccine roll-out began and 38 in 1960 (Blum et al, 2010: 2074).

Secondly and more crucially in terms of the diffusion of knowledge, the production of the patent free vaccine in Israel and other countries such as the Netherlands and Denmark led to important local level investments in vaccine technology by the public sector which helped sustain innovations in the polio vaccine that would not otherwise have been carried out by private companies (Blume, 2005). Examples of these include 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 collaboration on infectious diseases with the US and WHO (Goldbum, 1994; Blum et al, 2010). Similarly, the adoption and investment in Salk's vaccine by the Dutch Health

[6] The virus remains in circulation in three countries: Afghanistan, Pakistan and Nigeria (OChmann and Roser, 2017)

authorities, led to important innovations that addressed local production bottlenecks and led to an enhanced vaccine becoming available for other countries (Blume, 2005).

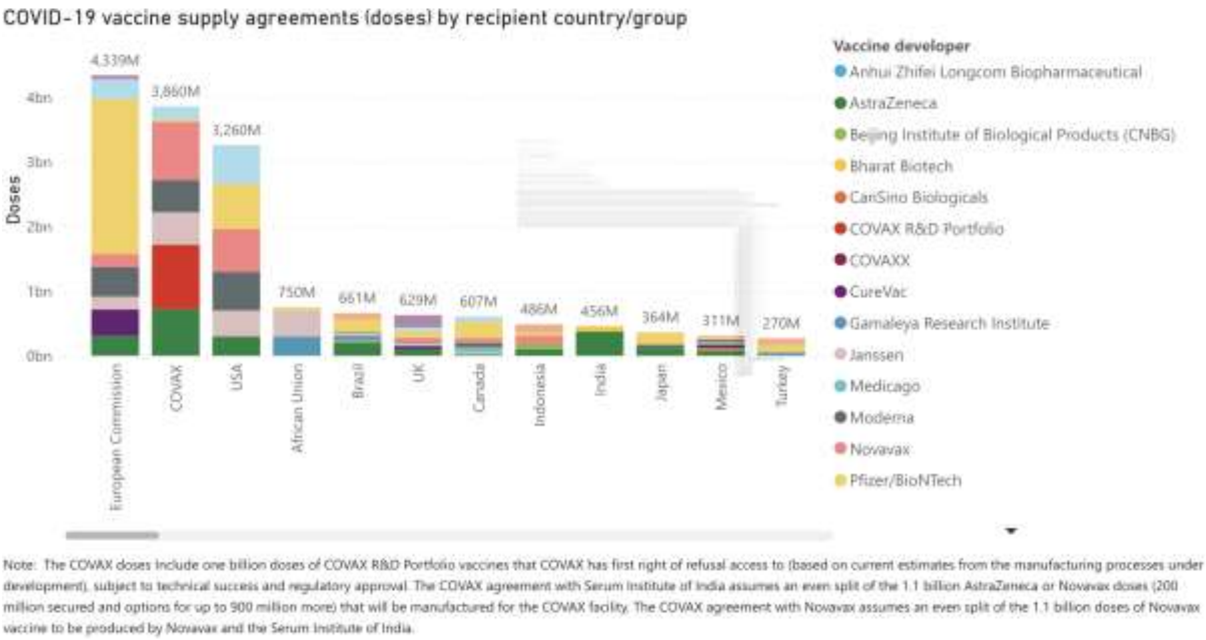
Vaccine Development and Diffusion for Covid19 post-TRIPS

The announcement by the WHO in March 2020 that Covid19 infections constituted a pandemic 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 (AGAs). 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, 2021). 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 Covid19 vaccines in less than 1 year was a remarkable collaborative achievement and one that has undoubtedly saved many lives and significantly reduced the cost of the pandemic.

The picture regarding diffusion is less rosy. The nature of the APAs has resulted in middle and high-income countries securing the vast majority of available vaccine doses, often attaining many times more than required for their populations, while low income countries have struggled to gain access. Figure 5 illustrates the inequality in vaccine diffusion with high income countries like the UK having almost 10 vaccines per capita while low income countries have close to zero. As predicted by the above game-theoretic analysis, vaccine supply has been cornered by bilateral country deals at the expense of multilateral deals designed to provide more equitable access.

Although vaccine development is characterised by different levels of complexity (e.g. Smith et al, 2011), 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 even if a patent waiver were to be agreed (at the time of writing this has not happened) the ability to diffuse production is severely limited.

Figure 5: Covid 19 Vaccine Supply Diffusion, June 2021



Source: UNICEF (2021)

4.2.3 Compulsory licensing under TRIPS and access to HIV/AIDS drugs

A third regulatory environment that can be considered concerns compulsory licensing. Compulsory licensing was introduced in 1995 as part of the TRIPS Agreement and involves allowing the use of a patented invention without the patents owner’s consent in order to improve access to essential inventions, for example, pharmaceutical drugs (e.g. Stavropoulou and Valletti, 2015). A compulsory license is not the same as a patent waiver as some compensation should still be paid to the license owner and CLs are restricted to domestic consumption. Moreover, countries seeking a waiver have to demonstrate that they have tried to strike a licence deal with the patent holder but have been unsuccessful. Hence, CL take some time to initiate. In developing countries CLs have been used with the aim of improving access to HIV/AIDS drugs (Song, 2019). Today, 38 million people globally live with HIV, and most of them (28 million) have 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 compulsory licensing 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 Wasta (2002) found that patents had a negative impact on access to antiretroviral drugs, by reducing competition and increasing prices. They estimated that, between 1995 and 1999, switching all HIV/AIDS drugs from a patent to a no patent regime would have increased access by at least 30% (Borrell and Watal, 2002: 5).[7] Similarly, a systematic review of the literature on compulsory licensing by Urias and Ramani (2020) concludes that it does reduce drug prices and improve access.

But compulsory licensing is not sufficient to achieve the payoffs from a cooperative strategy with capacity building (Figure 3). As discussed by Moser (2013), when using the compulsory license, countries do not have the knowledge transfer from the scientist and skilled workers who developed and implemented the original innovation. 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

[7] 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.

multiple countries (including middle income countries) in order to harness technology and innovation for the common good.

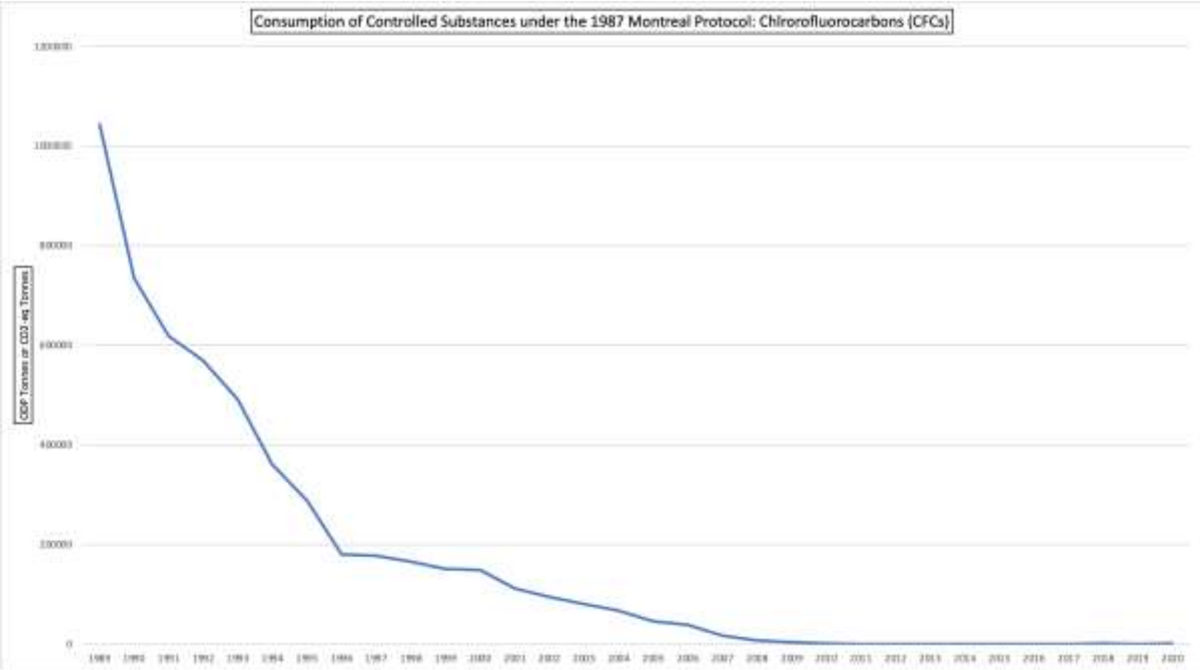
4.2 Natural Experiment 2: Environmental technologies for CFC Gases Under the Montreal Protocol and Low/Zero Emission Vehicles under TRIPS and the Paris Agreement

In the discussion below 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 petrol and diesel engines.

4.3.1 IPR and CFC Gases: the Montreal Protocol

The Montreal Protocol introduced in 1987 is the only Environmental Protocol ratified by all 198 UN Member states and is widely regarded as one of the most successful. The Agreement was introduced pre-TRIPS and included flexible instruments and incentives to encourage the discovery of replacements for CFC gases in order to prevent further damage to the Ozone layer. Initially, key players in the industry were skeptical about committing to the Protocol's cooperative regulatory framework arguing that, "we know of no good lead to the third generation technology, and believe that it will take several decades or more to bring such technologies into commercial production, once identified" (Du Ponts's evidence to a sub-committee of US Congress, cited in Moore (1990: 321). However, alternatives were found and within 5 years CFC emissions were more than halved as shown in Figure 6.

Figure 6 Consumption of Controlled Substances under the 1987 Montreal Protocol: CFCs



Source: UN Environment Programme Ozone Secretariat (2021)

Under the Protocol over US$3.9 billion has been invested in the *Multilateral Fund for the Implementation of the Montreal Protocol* established in 1991 to provide technological assistance supported by strong links between the science base and industry. 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), effectively removing IPR-based obstacles to diffusion.

De Sombrero (2000: 49) put the success of the Treaty down to 2 other factors: its flexibility and capacity to adjust to new situations and its engagement with the needs of developing economies. While there was uncertainty over the prospect of finding new technologies and substitutes the Treaty allowed for adjustments to meet changing needs. A central take-way point from this case study is while prior to regulation the industry said they needed decades to find substitute products, the Montreal Protocol led to many targets being met within 5 years by effectively removing the brake on diffusion emanating from patents and encouraging knowledge sharing and technology transfer. After 1995/6 most remaining CFC production was in developing economies who were given a longer time frame as well as technology and knowledge transfer support to help them eliminate CFC gases.

4.3.2 Low/Zero Emission Vehicles under TRIPS

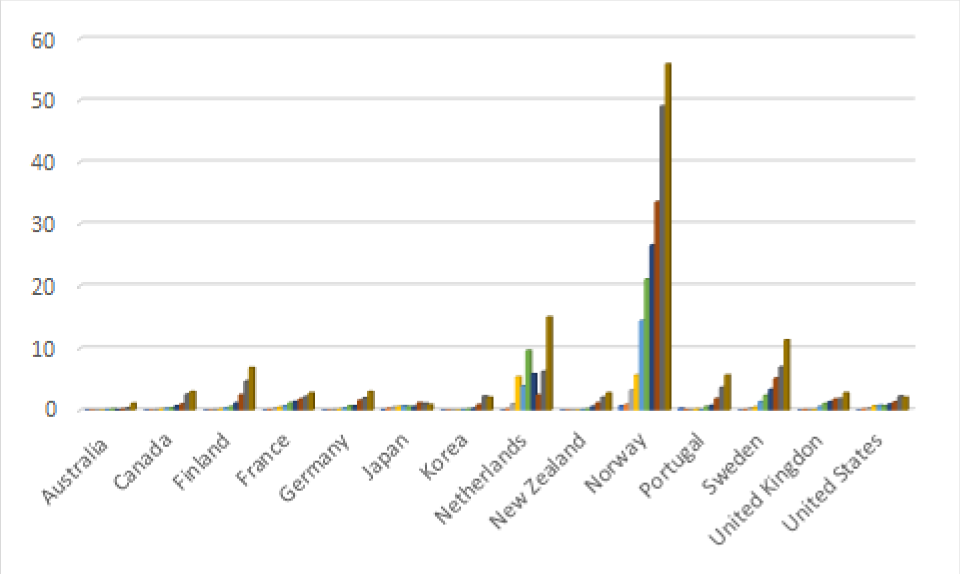
The Case of Electric vehicles

The case of EV technology also illustrates the importance of factors other than strong intellectual property rights, such as environmental regulation, to accelerate the adoption and diffusion of new low-carbon technologies. Today, countries as different as Norway and China in terms of their intellectual property rights regimes have some of the world's highest percentage of EVs in their fleets (Figure 7, EIA 2020).

The diffusion of EV technology in China has benefited from technology transfer within joint ventures with multinational firms, while at the same time Chinese firms have increased the number of patent applications especially in the area of battery technology (Kennedy, 2018). This has seen China achieve a relatively rapid diffusion of EVs (Figure 8). But it has also reinforced a highly uneven rate of technology diffusion in electric batteries, with the market for patenting technology in this area concentrated in China, Japan, the U.S., and Europe (Yuan and Li, 2021). As a result, China has become a relative outlier among other developing economies in terms of the diffusion of electric vehicles.

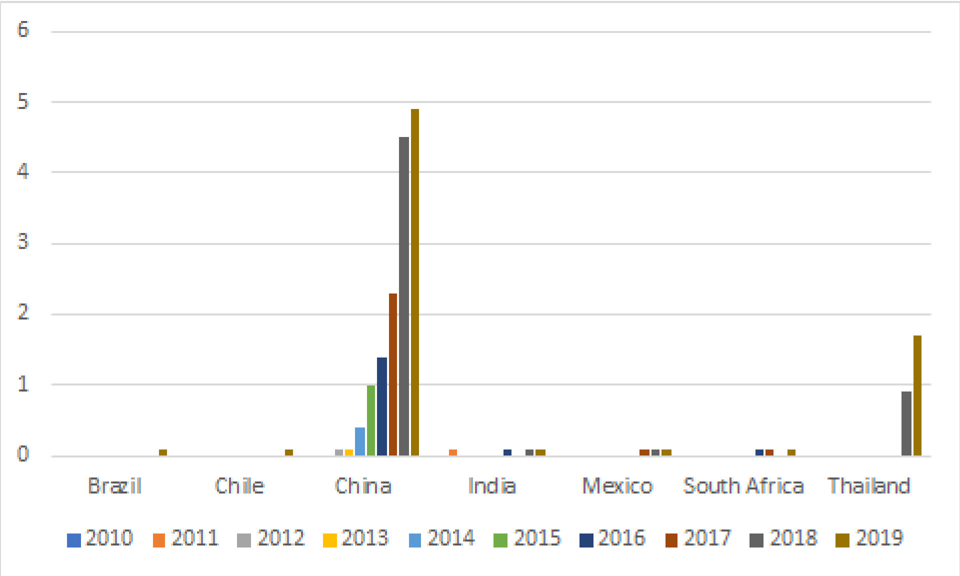
However, the uptake of EVs has been slow in most cases due to a number of factors including: (1) their higher cost; (2) their shorter driving range; (3) the required charging time; (4) the need for charging infrastructure; and 5) the failure to internalise the negative effects of internal combustion vehicles through policy interventions (Barton and Schütte, 2017: 150-151).

Figure 7: Market share (%) of electric vehicles (BEV and PHEV) in selected developed economies (2010-2019)



Source: Data adapted from IEA(2020: 250)

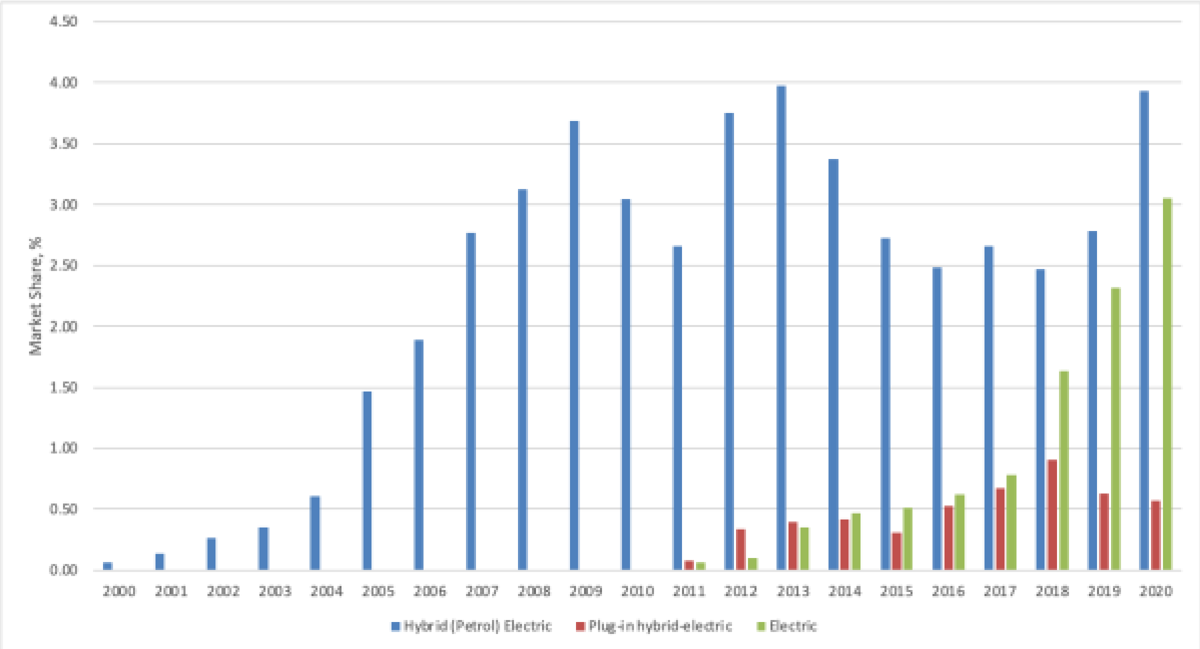
Figure 8: Market share (%) of electric vehicles (BEV and PHEV) in selected developing economies (2010-2019)



Source: Data adapted from IEA(2020: 250)

Some subnational, national and supranational jurisdictions, however, have been relatively more successful than others in overcoming these barriers and creating strong incentives to transition to EVs. Examples include California, Norway, China and the EU (Barton and Schütte, 2017; Li et al, 2018; Zimm, 2021). Figure 9 illustrates the very slow diffusion of hybrid cars since their introduction in the US in 2000. Some 20 years later the share of hybrid, plug-in hybrid and electric vehicles combined is just 7.6 per cent. Barton and Schütte (2017) highlight the effectiveness of fuel efficiency or greenhouse-gas emissions standards as a policy instrument to encourage the diffusion of EV technology. The effect of tighter regulation in California has led to double the US market share in California (now at 15 per cent) largely as a result of the California Air Resources Board's Zero Emission Vehicles regulation which has set targets for the market share of Hybrid EV and ZEV vehicles since 1990. The latest regulation requires larger manufacturers to increase their share of Zero Emission Vehicles to 22 per cent by 2025 (CARB, 2021).

Figure 9 Market Share of Petrol Hybrid-Electric, Plug-in Hybrid and Electric Vehicles, United States, 2000-2020



Source: Adapted from US Department of Energy (2021)

5. Towards a Taxonomy: Policy Implications and the Case of CPRs

Technological progress has long been central to improving living standards. Yet technology is increasingly becoming a source of inequality of opportunity. Our analysis highlights the absence of an appropriate diffusion mechanism for technologies related to CPRs. Underpinning this inequality of opportunity is a lack of appropriate diffusion mechanisms consistent with the complex architecture where the diffusion of knowledge-based capabilities and policy regulation are central to innovation (Orsatti et al, 2020; Horback, 2008; Porter and van der Linde, 1995). Resolving the anomalies in the post-TRIPS patent system requires policy makers to address both aspects of this by re-configuring the patent system to tip the balance in favour of diffusion and developing a system of global coordination.

Drawing on our taxonomy (Table 1), we suggest that for inventions and technologies that protect CPRs (i.e. Class 6), the granting of patents should only occur where it can be demonstrated that there is no infringement on the public interest and that a certain level of diffusion can be achieved. This would need to involve a mapping of resources and capabilities so that opportunities for greater public buy-in could be identified.

Our analysis suggests several obstacles related to the patent system that prevent firms, especially in low income countries from going out and fishing in the sea of opportunities (e.g. Dosi et al, 2006). For policy to improve these opportunities and promote innovation to protect CPRs, investment in R&D capacity alone will not be sufficient but also requires a focus on complementary assets and infrastructure (Teece, 1986). While it has long been recognised that there is significant potential for resourcing public sector vaccine agencies in both developed and developing countries, it has generally been accepted that most vaccines of interest will be developed in advanced economies by private companies (Hausdorff, 1996). This is not because vaccines are unattractive to manufacture, but rather because for most vaccines, even those whose manufacture is not protected by patents, research and development costs, industrial know-how, and the associated costs represent high barriers to entry (Smith et al, 2011).

Policy prescriptions for addressing these problems tend to focus on addressing learning poverty at the grassroots level (e.g. the World Bank's Accelerator programme) or global immunity programmes. Our analysis indicates that it is important to pose the question of whether more could be done to quicken the rollout of vaccines and green technologies? Current approaches based on the COVID-19 Vaccines Global Access (COVAX), GAVI (the Vaccine Alliance), and CEPI (the Coalition for Epidemic Preparedness Innovations) have the objective of vaccinating 20 per cent of the global population (Bown and Bollky, 2021). It is important to acknowledge the success of GAVI in achieving high immunisation rates against hepatitis B, H influenzae type b infection, and pertussis in the 72 participating countries (Smith et al, 2011). Yet the success of GAVI has also highlighted a lack of progress in building capacity for more complex vaccines under the Expanded Programme on Immunization, causing developing economies to lag behind wealthier economies in the early years of license (Smith et al, 2011). At the time of writing no low income economy has sought to compulsory license the production of a COVID vaccine, illustrating our argument that for research policy, a compulsory licensing system is not sufficient in itself for faster diffusion. This is not surprising given the general reluctance of developing economies to engage in the TRIPS process and the lack of established patent systems.

If developing economies are reluctant to engage in compulsory licensing or lack the capabilities for vaccine production, should policy makers take a different approach to protecting common pool resources? Previous efforts to diffuse and promote innovation in the development of vaccines prior to TRIPS offers an important counterfactual, in particular illustrating the importance of promoting the diffusion of capabilities to address network externalities. Salk's unpatented polio vaccine in the 1950s led to innovations in local vaccination practices and ability to circumvent the problem of local production bottlenecks (Blume, 2005). This seems particularly important in the current environment given the general problem of shortages in vaccine production capacity (WHO, 2020), and specific supply chain issues is supplying key inputs for vaccine production such as lipid nanoparticles, which have their own specialized supply chains (Bown and Bollyky, 2021).

A second alternative could focus on improving the system of patent pools and pledges for environmental technologies by asking how can the IRP system be adapted to accommodate the diffusion of these technologies and how can the patent pledge system be resourced to ensure a better success rate? A key advantage of *patent commons* for diffusing technologies is their ability to confer benefits on third parties regardless of contribution to the commons and the absence of formal contracts. What they lack is tracking and dedicated administrative and managerial resources designed to promote their usage (Contreas et al, 2018). To effectively diffuse green technologies, these initiatives will require investment in administrative and technical support to give similar publicity and appropriability advantages to the patent system. A second area of improvement concerns the overall design of incentives. Clugston (2021) argues that, based on the failure of royalty free eco-patent commons to garner sufficient interest, key to improving the design of these programmes is to ensure that they maximise the value of intellectual property assets for both contributors and users. Given the scale of the climate challenge and the need to diffuse green technology rapidly, the fee structure for these programmes would need to be largely borne by developed economies in order to encourage participation from low income countries (Clugston, 2021). One way of achieving this would be through subsidies and public support.

6. Discussion and Concluding Comments

In the case of CPRs, the patent system does not function very well. It is disappointing that more than a century after the patent system became the cornerstone of protection for inventors, little has been done to correct the anomalies and distortions that it has created for the diffusion of certain technologies. Global coordination issues have stalled the use of green technologies such as electric vehicles, while compulsory licensing remains underused by developing economies. Our conceptual framework in this paper indicates that in correcting these issues, the patent system must be seen in the wider context of the innovation system. This includes the regulatory and institutional environment and its effectiveness is therefore context dependent. We need a more granular approach and one that recognises that for technologies to protect CPRs and meet global challenges patents are counterproductive because slowing down diffusion undermines their effectiveness.

We propose a taxonomy of patents that may be used to assess when the resolution of the patents paradox should fall on the side of diffusion, rather than R&D incentives. We theorise that in the case of CPRs, such as public health the interests of society are best served by prioritising diffusion. In fact, IPRs are counterproductive for CPRs. We bring empirical evidence to bear on this proposition by considering a natural experiment of two case studies of a global pandemic: one without patents/IPR (polio) and one with patents (Covid19). We also consider evidence from the intermediate case of HIV/AIDS drugs that were subject to patents but also used compulsory licensing. We note in all cases IPR is only one limit on diffusion. Other constraints come from transferring the knowledge and technology, whether under license or freely. We find evidence that this is easier to do in an open system (without IPR- as in the polio case). We find that knowledge and technological capability to manufacture vaccines was much quicker in the polio case without IPR.

We also find that in the case of Hybrid and EV technology that diffusion has been slow - imposing significant costs on society in the form of cumulative CO_2 emissions. We compare the case of California with the rest of the US and other countries and show the *key* role played by the regulatory environment under the same TRIPs laws. Again this provides a similar type of natural experiment with and without environmentally friendly regulation.

The key policy message from our empirical analysis in the case of vaccines for global pandemics suggest that IPR should be immediately waived as soon as a Pandemic is announced and that knowledge and technology transfer should be supported by policy measures to strengthen innovation systems across the globe. This would also help promote catch-up. In the case of green technologies, our findings indicate that diffusion could be speeded up by non-patent regulations e.g. California, Norway-type laws, but that even in these cases diffusion is slow. This highlights the strong case for a fully resourced patents commons for green technologies that is underpinned by strong regulation (e.g. as in CFC gases) and policies to transfer knowledge and technology. Ultimately this will require a strengthening of international governance and institutional cooperation at a level unseen since Bretton Woods.

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