Centre for Technology Management working paper series
ISSN 2058-8887

No. 3
August 2024

Intellectual property models for sustainability transitions: A multi-level perspective

https://doi.org/10.17863/CAM.111359

Akriti Jain *
Pratheeba Vimalnath
Anjula Gurtoo
Frank Tietze

* Please contact the corresponding author for feedback:
akriti.jain@imi.edu

Intellectual property models for sustainability transitions: A multi-level perspective

Akriti Jain[a], Pratheeba Vimalnath[b], Anjula Gurtoo[c], and Frank Tietze[d]

[a] International Management Institute – New Delhi, India

[b] University of Exeter Business School – Exeter, United Kingdom

[c] Centre for Society and Policy, Indian Institute of Science – Bengaluru, India

[d] Innovation and IP Management Laboratory, Centre for Technology Management, Institute for Manufacturing, University of Cambridge – Cambridge, United Kingdom

Abstract

Meeting the 2030 Sustainable Development Goals necessitates accelerated sustainability transitions through eco-friendly production-consumption patterns. This paper delves into the underexplored role of Intellectual Property (IP) in Sustainability Transitions (ST), specifically in Green Technologies (GT). Despite the recognized significance of IP in conventional technology transitions and the acknowledged role of innovation, particularly collaborative innovation, in achieving sustainability transitions, its application in the complex GT development and diffusion process remains overlooked. The study integrates Geels' (2002) Multi-Level Perspective (MLP) with Vimalnath et al.'s (2017) IP model typology, dissecting IP models within Socio-Technical System (STS) across spatial and temporal dimensions. Employing a solar photovoltaic case study structured along the MLP model and analyzed through Vimalnath's IP sharing model, the research identifies eleven propositions for IP models in different sustainability transition phases. Supported by additional examples, these findings offer a systematic exploration of IP's interaction with the ST process, offering valuable policy and managerial implications. While drawn from a single case study, these propositions provide a foundation for subsequent research to affirm their generalizability.

Keywords: *Intellectual property; Green technologies; Multi-level Perspective; Solar Photovoltaic technology; Sustainability transitions*

1. Introduction

The sustainability transitions (STs) concept has gained prominence, in contemporary discourse, marking a societal shift towards sustainability (Geels et al., 2017; Markard et al., 2012). STs differ significantly from conventional technology transitions. Unlike traditional technology transitions, STs is more complex requiring specific transformations towards the direction of environmental and social sustainability. The shift towards environmental sustainability necessitates the development, adoption, and large-scale diffusion of Green Technologies (GT), i.e., eco-friendly solutions for positive environmental impacts (Köhler et al., 2019; Markard et al., 2012). STs are characterized by long-term, multi-actor, multi-dimensional, co-evolutionary, unfolding gradually over decades and involving various stakeholders (Hernandez Chea et al., 2020; Köhler et al., 2019). STs occur when system components (like actor groups, infrastructure, and institutions) realign around new values, functions, and structures for sustainability (Farla et al., 2012).

Intellectual Property (IP) plays a pivotal role in this context, acting as a facilitator for GT development and dissemination (Siltaloppi and Ballardini, 2023) among socio-technical system (STS) actors, such as universities, research institutes, industries, firms, and governments (Eppinger et al., 2021; Jain and Gurtoo, 2021). While scholars have developed models to embed GT in societal systems for ST ((Kemp, 1994), there exists a significant gap in understanding how IP functions within the broader dynamics of ST (Siltaloppi and Ballardini, 2023). This paper addresses the gap by adopting an IP-centric perspective on ST, exploring how STS actors utilize various IP types, such as licensing patents or trademarks, to facilitate sustainability transitions.

Existing literature identifies diverse IP sharing models (Tietze et al., 2017); use of open source models of IP for sustainability (Sternkopf et al., 2016); and the role of IP in climate change mitigation technology (Raiser et al., 2017), plant breeding technology (Smulders et al., 2021), and geoengineering (Reynolds et al., 2018) among others. Despite IP playing an enormous role across various industrial sectors like semiconductor and biotechnology, the application of IP in the GT development and diffusion for systematic ST processes remains inadequately understood (Siltaloppi and Ballardini, 2023). The paper aims to bridge this gap, investigating how actors within STS use IP to protect, collaborate, and diffuse GT during the ST process. Proponents argue that IP facilitates GT development and diffusion, like other technologies ((Chavez, 2015)Raiser et al., 2017; Sarnoff, 2013)). However, others highlight barriers like patent thickets and anti-commons hindering GT development and diffusion (Chavez, 2015). This debate necessitates a systematic study to explore the application of IP by multi-actors in an STS for GT protection, collaboration, and diffusion (Siltaloppi and Ballardini, 2023)

Responding to this need, we adopt Geels' Multi-Level Perspective (MLP) model (Geels, 2002), a robust framework for studying ST (Turnheim et al., 2020). The MLP model allows exploration of multi-actor-driven shifts in STS along temporal and spatial dimensions, offering a comprehensive view beyond technological or economical aspects (Wilkinson et al., 2020). The MLP framework is widely used to study shifts in user behaviors, technologies, regulations, and infrastructures (Geels, 2002; Geels and Schot, 2007), using historical case-studies like hygiene, aviation and mobility transformation, among others (F. Geels, 2005; F. W. Geels, 2005; Geels, 2006a; Verbong and Geels, 2007) its use in systematic exploration of IP models and sharing mechanisms along the temporal and spatial dimensions of the within an STS is limited.

This paper leverages the MLP framework to study how STS actors utilize different IP models for the development and diffusion of GT for ST. In this context, the 'IP model' refers to how an actor controls the ownership, access, and usage rights of relevant IP assets, e.g., patents, trademarks, design rights, to achieve a specific purpose (Vimalnath et al., 2020).

The exploratory case study focuses on solar photovoltaic (PV) technology, a prime exemplar of GT facilitating energy transition. Solar PV has played a crucial role in the global energy transition, witnessing exponential growth (Verbong and Geels, 2007). From 1990 to 2020, global electricity generation using solar PV increased by a factor of almost five thousand, while from all other fuels during the same period it increased by around 2.3, highlighting its prominence in sustainable energy production (Haegel and Kurtz, 2021). Concentrating on solar PV, we analyze the IP models employed by STS actors, including firms, universities, research institutes, and governments, at spatial (levels) and temporal (phases) dimensions of ST. Case study findings and literature-based evidence led to propositions regarding IP models and their interaction with ST.

This paper contributes to ST literature by offering a structured approach to study IP models and their interaction with ST processes, using the MLP framework. The study integrates an IP perspective into the MLP framework, providing valuable policy and managerial implications. Policymakers can design interventions fostering innovation and accelerating GT adoption by understanding the nuances of IP models in sustainability transitions. Organizations can refine their IP models to align with sustainability goals.

The paper unfolds in sections, starting with a literature review highlighting existing gaps in understanding IP's role in ST. Section 3 outlines the methodology, followed by Section 4 presenting the solar PV case study. Section 5 frames propositions of IP models for ST based on case study findings and illustrative examples. Section 6 discusses findings with policy and managerial implications.

2. Theoretical Background

Four conceptual approaches—Multilevel Perspective (MLP) (Geels, 2002), Strategic Niche Management (SNM) (Kemp et al., 1998), Transition Management (TM) (Loorbach, 2010) and Technological Innovation System (TIS) (Markard and Truffer, 2008) —capture transition dynamics. While SNM and TM are policy-centric approaches, TIS and MLP emphasize organizational and technological innovation dynamics (Laukkanen and Patala, 2014). Geels' MLP framework, recognized for its robustness and flexibility, extends TIS by explicitly incorporating the user's role, emphasizing technology diffusion, impact, and societal transformation (Turnheim et al., 2020). Unlike TIS, which predominantly focuses on technology development, MLP provides a holistic view of ST by integrating the demand side.

2.1. Multi-Level Perspective and sustainability transitions phases

The Multi-Level Perspective (MLP) framework, introduced by Geels (Geels, 2002), outlines transition dynamics in three levels: niche, regime, and landscape. Niches act as protected spaces fostering experimentation and innovation, breaking lock-ins and path dependencies (Geels, 2011). Regimes encompass established systems, defining rules, routines, culture, and practices, while landscape dynamics involve exogenous factors like globalization and climate change, exerting pressure on regime and niche levels ((Geels, 2004).

Geels, (2019) visualizes MLP-based transition pathways as S-like curves, progressing from slow-moving changes to stabilization, forming new socio-technical systems. The MLP model comprises four phases. The Experimentation phase involves proofs of concepts, pre-competitive research, and entrepreneurial endeavors, characterized by new knowledge, investments, partnerships, and innovation races (Geels and Schot, 2007). In GTs, this phase is prolonged due to market imperfections hindering private investment in green R&D.

The Stabilization phase sees the emergence of a dominant design from the niche, attracting players from various fields, and creating a temporary pilot market with policy support (Jacobsson and Bergek, 2011). GTs face challenges, such as network externalities and lobbying against sustainability (Geels, 2019). In the Diffusion phase, economic competition, technological developments, cost reduction, and standardization occur, with GTs addressing mass-market integration challenges (Raiser et al., 2017).

Institutionalization follows, involving awareness campaigns, educational programs, policy advocacy, and industry standards (Geels, 2019). R&D, energy conservation, and IP policies significantly contribute to GT institutionalization, distinguishing it from conventional technologies primarily diffusing for immediate economic benefits (Plooy, 2013).

2.2. *Challenges Unique to Green Technologies: Necessity of Innovative IP Models*

Green technologies present unique challenges distinct from conventional non-green technologies. GTs exhibit impure public-good characteristics, combining individual benefits (e.g., electricity provisions) with public benefits (e.g., environmental conservation). However, unlike conventional technologies, improving GTs may not always increase demand due to the availability of substitutes (Kotchen, 2005). Private players, therefore, may have little incentive to invest in GT niches. GTs tend to have slow-moving development. They initially rate lower on price/performance ratio than conventional counterparts but experience significant cost reduction in core module and performance improvement (Malhotra and Schmidt, 2020). Their multidisciplinary and general-purpose nature calls for extensive collaborations outside the supply chain, among multiple actors like research institutes, universities, and competitors. Moreover, GTs create double externalities leading to higher costs for firms investing in them, which can lead to sub-optimal private investment and market failure (Ghisetti et al., 2015; Horbach et al., 2013; Rennings, 2000). These complexities necessitate innovative IP models and regulatory interventions to promote GTs adoption and diffusion. While IP systems were traditionally viewed for exclusive commercial exploitation, they now function as collaborative tools encouraging joint development and technology diffusion (Siltaloppi and Ballardini, 2023; Jain and Gurtoo, 2021)

2.3. *Intellectual Property models*

The evolution of IP systems from allowing exclusive commercial exploitation of an invention for a specific period in return for public disclosure (Kieff, 2005), to a collaborative and sharing tool is evident. Actors exchange or share IP assets (registered formal IP like patents, trademarks, industrial rights; and unregistered informal like know-how and trade secrets) to access, develop and diffuse novel technologies (Klingenberg and Watson, 2010).

Vimalnath et al., (2020b) proposed a typology for IP models. Closed IP models refer to the internal and exclusive use of formal and informal IP assets without external sharing. Semi-open IP models, like exclusive licensing (Liddicoat, 2017) non- exclusive licensing (Beyer, 2013), enable sharing with selected partners. Semi-open IP models also include open patent pools (Boutin, 2016), copyleft licenses (e.g., CC-BY-NC license) that allow conditional sharing of IP assets with a broad set of actors allowing-public access and dissemination with commercial or use-related restrictions or conditions. Some examples of this model include the Linux' open-source model for operating system development (Henkel, 2006), royalty free licensing, open patent pools (Ehrnsperger and Tietze, 2019; Eppinger, 2015) and patent pledges (Contreras et al., 2020, 2019) (e.g., Open Covid Pledge).

Fully open IP models (Bissell, 2009), including CC-0 or public domain license includes unconditional sharing of IP assets by releasing the IP in the public domain. It involves providing access to IP free of cost without any commercial or usage restrictions. Examples of such IP models include IP donations (Ziegler et al., 2014), IP abandonments, making IP freely available without restrictions (Baker and Mezzetti, 2005). Firms tend to adopt semi-open-1 IP model when they lack complementary technology assets (Pisano and Teece, 2007), and when in-house technology development and diffusion becomes challenging, costlier and time taking (Chesbrough, 2003).

Prominent studies on IP for GTs, (e.g., (Lema and Lema, 2012) studying fuel cells, wind, water, and solar energy; (Kim, 2003) internet infrastructure; (Suh et al., 2020), mobility, waste management, and (Moreno et al., 2019) recycling) use patent applications or citations to analyze the growth trend in the respective GT fields. Conceptual framework connecting micro-level IP models and sharing mechanism of system actors like firms, universities, research institutes and public bodies supporting broader system change is missing from the literature.

3. Methodology

The research employs a single case study method to harness rich historical insights, conducting an in-depth examination of a specific phenomenon, as opposed to broad analyses (Eisenhardt, 1989; Yin, 1994). This methodology aligns with Gerring's definition of presenting "an intensive study of a single unit for the purpose of understanding a larger class of (similar) units" (Gerring, 2004, p. 342). Utilizing case study methodology facilitates a comprehensive exploration of context-specific factors, process-tracing, and outcomes (Gerring, 2004), that addresses challenges like limited generalizability and biases in historical records through triangulation (Eisenhardt, 1989). Qualitative single case studies have previously offered valuable insights into diverse phenomena e.g., bankruptcy in Silicon Valley (Sutton and Callahan, 1987), technological change and dynamic capabilities of NCR Corporation (Rosenbloom, 2000), among others. Additionally, single case studies have previously been used in utilizing MLP framework to effectively capture systematic shifts in socio-technical systems (STS) components through niche, regime, and landscape developments (F. Geels, 2005; F. W. Geels, 2005; Geels, 2006a, 2006b).

The chosen case study in this research focuses on solar photovoltaic (PV) technology, driven by its long history, policy implications, and theoretical significance in sustainability transitions. Solar PV's adoption has spurred policy innovations like Germany's Energiewende and complementary technological advancements, including smart grids, batteries, smart meters, and storage technologies (Geels et al., 2017). The evolution of solar PV technology has been well-documented, providing us with a wealth of data to analyse, interpret, and identify patterns, trends facilitating a nuanced understanding of the IP models that have shaped its trajectory.

We present an analysis of solar PV technology from its emergence in 1839 to 2018 to trace the evolution of the technology and the (ongoing) energy transition through different phases, as outlined in Geels' MLP framework. Examining this lengthy period enables capturing nuances in policy innovations, technological advancements, IP models, and business model innovations within the sector.

We adopted a two-step approach to identify IP models for system-level ST.

In *step 1,* we present a historical case study of solar PV technology's emergence, growth, and diffusion, with a focus on IP models and sharing mechanisms of relevant STS actors using the MLP framework. Creating a chronologically structured dataset of solar PV technology involved systematically collecting secondary data from diverse sources, including peer-reviewed papers, books, and further cross-referencing company websites, press releases, industry reports, and media articles. We identified 1192 peer-reviewed papers, book chapters, and conference papers using terms like (“Solar” OR “PV” AND “intellectual property” OR “IP”), (“photovoltaic” OR “PV” AND “intellectual property” OR “IP”), (“solar PV” AND “intellectual property” AND “transition”), (“photovoltaic” AND “intellectual property” AND “transition”), among others on Scopus and Google scholar. After narrowing the search scope (to the social science, arts and humanities and business management discipline, and analyse of innovations and IPR related aspects of solar PV technology), 31 relevant papers were selected. We cross-referenced with books, media articles, and government agency reports to create the final dataset of 94 documents e.g. (Barton et al., 2007; Jones and Bouamane, 2012; Kumar, 2020; Lee and Hess, 2019; Nemet, 2019). We cross-verified the interpretation of the solar PV technology evolution, growth, and STS dynamics through expert feedback over two years i.e. 2021-2023 from over 25 IP and sustainability professional, researchers, and expert ensuring data reliability.

Step 2 involves building propositions based on case study findings and discussing literature-based illustrative examples of GTs beyond solar PV. These propositions demonstrate IP models of system actors at different STS levels along the four phases of the MLP framework. The illustrative examples taken from the literature are of different GTs and sectors, exhibiting similarities to our case study findings, thus ensuring the internal validity, and generalizability of propositions (Eisenhardt, 1989).

4. Case study: IP sharing models for solar PV technology facilitating energy transition

The historical accounts of energy transition demonstrate the increasing contribution of renewables by almost 50% in global power generation (Gales et al., 2007). Among various alternatives of renewable energy like solar, wind, fuel cell, among others, the solar PV technology has experienced a significant growth in innovations and total published patent cooperation treaty (PCT) applications during 2002-2019 (i.e. from 26% of total PCT applications in 2002 to more than half 2010 onwards, see Figure 1) facilitating energy transition.

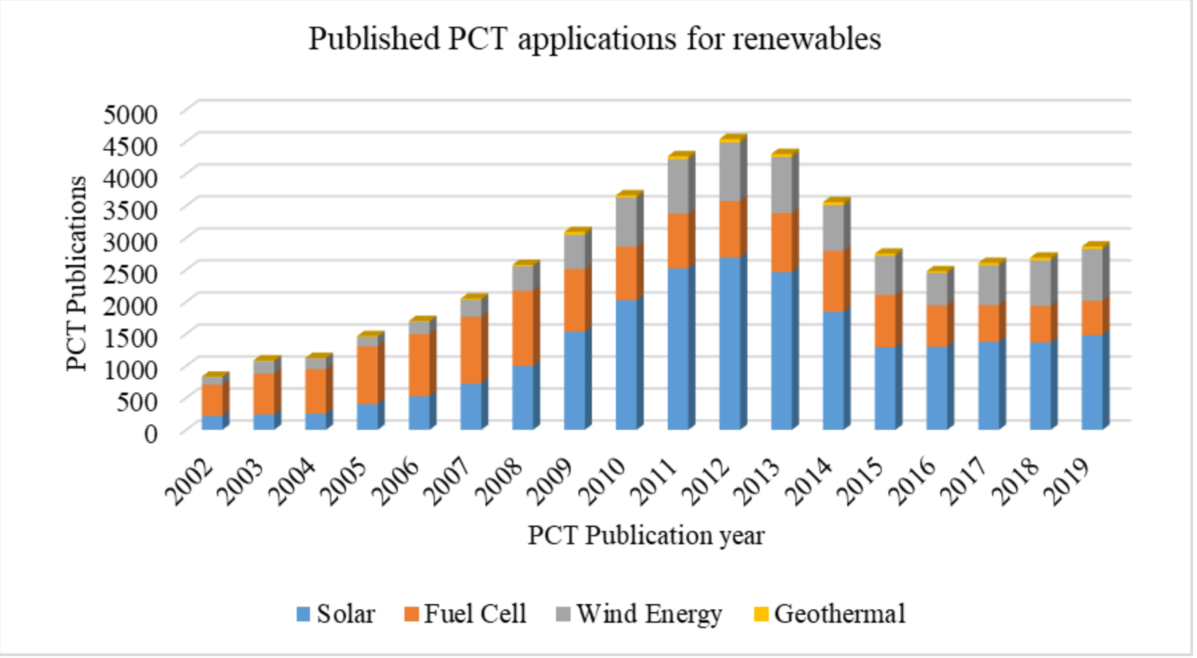


Figure 1: Published PCT (Patent Cooperation Tyreaty) publications for renewables (2002-2019)
Source: Economics and Statistics Division, WIPO

Below we describe a case study of emergence and growth of the solar PV technology to demonstrate the select IP models of actors of STS at spatial and temporal levels of the (ongoing) energy transition. Adopting the pattern of Geels (2005) we organize the factual depiction of the solar PV case into four sub-sections corresponding to the four phases of the multi-level perspective.

4.1. Emergence of the Solar Technology Niche: Early Dynamics and IP Models (1839-1960)

The earliest discovery of the photoelectric effect in 1839 towards 1956 involved pre-competitive, non-commercial research through which early technology niches were created in small pockets in the US and France (Geels and Schot, 2007). In France, Edmund Becquerel's discovery of the photoelectric effect ignited interest in harnessing solar energy, motivating scientists and policymakers to delve into solar energy techniques, and thus started the solar technology niche creation ("How the solar cell found the spotlight," 2019). The increased interest in solar technology is evident in the publication of approximately 50 publications between1880 and 1914 in *Scientific American*, an influential science magazine (Kumar, 2020), These dynamics illustrate the spirit of scientific knowledge generation, dissemination, and open science and an **open IP model** during the initial part of the experimentation phase**.**

As the experimentation progresses, individual inventors, university scientists, and private research labs engage in applied research and prototype development (Geels and Schot, 2007), fostering solar PV technology in ‘pockets’ across the US and France. Post-1890, small firms emerged, providing solar water heaters for household and agriculture applications (Kumar, 2020). Mathematician August Mouchet, funded by the French government, invented a solar steam-powered printing press and patented the use of concentrated solar radiation to heat water in 1860. Edward Weston secured the first two U.S. patents for solar devices (U.S. 389124, U.S. 389125). However, it took 76 years to monetize, with Bell Labs filing patents in 1954 for the first silicon solar PV cell and building the inaugural solar panel (“How the solar cell found the spotlight,” 2019).

In the latter part of the experimentation phase (1930-1960), observations reveal a shift to patent-based, closed IP models by individuals, entrepreneurs, and private labs, protecting privately funded R&D outcomes (Beise-Zee, 2004). Innovation policy instruments had limited intervention, and there's no indication of higher-level IP use during this phase. Table 1 illustrates various IP sharing models during the experimentation phase, highlighting the coexistence of open and closed IP approaches among diverse actors at different levels.

Table 1 IP sharing models in Emergence of the Solar Technology Niche **(1839-1960)**

Levels	**Actors**	**IP sharing models**	**Examples**
Niche	Individual inventors	Open IP model	Edmund Becquerel published the discovery of the photoelectric effect
Niche + Regime (Direct R&D funding)	Individual inventor + Government	Closed, patent-based IP models	August Mouchet developed a prototype of solar-powered devices after receiving government funds, and filed several patents
Niche	Individual inventors		Edward Weston in 1860 received two US patents on solar-powered devices
		Open IP model	Charles Frits created the first solar cell, i.e. patents were applied for but were not granted
	University and Independent researchers	Open IP model	Around fifty publications on solar energy were featured in Scientific American
	Entrepreneurial start-ups	Closed IP model to protect internal R&D	Numerous solar water companies, including Climax Solar Water Heater (1891), Solar Motor Company (1892), and Day and Night Solar Hot Water Heater (1892), were founded
	Private company		Bell Laboratories patented the first silicon solar cell as "Light sensitive device" in 1954

4.2. Pilot market creation, dominance of silicon solar cell and emergence of industry associations (1956 - mid 1990s)

Landscape changes, driven by concerns about fossil fuels and the 1973-74 oil crisis, facilitated the entry of established players and startups into the solar PV niche. The US government's demand for satellite applications in the 1956-1960 period created an early pilot market for solar PV. Policy interventions, like Japan's Sunshine Program (1973) and the US Solar Energy R&D and Demonstration Act, shaped solar energy's trajectory. Initiatives like the National Renewable Energy Laboratory (NREL, 1977) and the Bayh-Dole Act (1980) stimulated partnerships and technology transfer. From 1974, patented amorphous silicon solar cell technology, pioneered by David E. Carlson at RCA labs, dominated, with Walter Spear and Peter Le Comber enhancing efficiency(SPIE - The International Society for Optics and Photonics, 2013). In the 1980s, Swiss engineer Markus Real, established Europe's first grid-coupled solar system, while the US saw large-scale terrestrial PV projects, including the notable 6.5 MW Carrisa Plains facility. Established Electronics and semiconductor firms like Hoffman Electronics, Texas Instruments, RCA labs, Sharp, Exxon, Mobil, Amoco, and Arco entered the solar field, adopting **closed and semi-open IP models** (internal R&D, IP acquisitions, exclusive in-& out-licensing, IP co-development and co-ownership). Sharp, from the semiconductor or electronics industry, for example adopted the closed IP models, i.e. protecting internal R&D, but also accessed IP through acquisitions for internal exploitation to enter what was still a niche ((Jones and Bouamane, 2012).

Table 2 IP sharing models in pilot market creation, emergence of dominant design and industry association **(1956-1995)**

Levels	**Actors**	**IP sharing models**	**Examples**
Niche & Regime (New industry formation supported by changing policy and technology regime) Sunshine program in Japan in 1973; Solar Energy R&D and Demonstration Act, 1974 in US ; Establishment of National Renewable Energy Laboratory (NREL) in the US 1977; Public Utility Regulatory Policies Act (PURPA) and the Energy Act, 1978; US Bayh-Dole Act, 1980 ; R&D subsidies, Public procurement, energy tax, technology support programs, political endorsements	Entry of MNCs and small firms, Start-ups, university spin-offs and private labs from related & unrelated technologies	Closed IP model (patenting to protect internal R&D) Semi-open IP model (exclusive in- & out-licensing to company and university spinoffs, collaboration, and co-development)	- National Fabricated Product (NFP) in Chicago purchased the licensing rights of the Bell PV patent, which Hoffman Electronics later acquired to commercialize solar PV cells to US satellite. - An entrepreneurial venture, Solarex invented and patented, through internal R&D, high-efficiency solar cells & their production process. Subsequently, Solarex collaborated with Japanese firms and provided Dutch and French electrical firms manufacturing licenses to commercialize PV cells in the European market. - In 1981, licensing-out of two university patents in Spain created a start-up, Isofoton, to develop and produce solar cells. The Company[1] adopted a combination of closed and semi-open 1 IP model through internal and collaborative R&D, patenting, and exclusive in- & out-licensing. - Entrepreneurial venture Spectrolab through internal R&D started providing solar panels for the US air force. Large semiconductor firm Textron later acquired the Company, along with its technical know-how - Radio Corporation of America (RCA) labs & Texas instruments filed multiple patents through **internal R&D** separately. - RCA labs first patented and demonstrated the application of amorphous silicon solar cells in 1977 - Japanese electronics venture Sharp developed solar cells through internal R&D for multiple application during 1960-80.

[1] https://www.wipo.int/wipo_magazine/en/2009/02/article_0008.html

New ventures like Spectrolabs and Solarex also adopted a combination of **closed and semi-open IP models**. For instance, they out-licensed or sold-out the technology to large firms in related fields for commercialization (SPIE - The International Society for Optics and Photonics, 2013) (see Table 2). Industry associations, such as the Japan Solar PV Energy Association (1987) (comprising (Kyocera, Sanyo, Matsushita & Sharp) and Solar Energy Industry Association (US) and European Photovoltaic Industry Association (France) in 1974 and 1985 respectively, reflected collaborative efforts in green technology development (Jones and Bouamane, 2012).

4.3. Towards diffusion of solar PV and partial replacement of the conventional energy system (1995- late 2010s)

The genesis of mass-market formation in solar technologies began with value chain establishment, enhanced efficiency, and cost reductions (Jones and Bouamane, 2012). Post-1995, solar technology patenting surged by 20% annually (United Nations Environment Program (UNEP), 2010). Q-Cells, Solar Millenium, and SolarWorld initiated large-scale solar power plants in 1998, adopting a semi-open IP model during 2006-2018 (see Table 3)**.** This involved informal IP exchange, know-how transfer, non-exclusive in- & out-licensing, cross-licensing, IP sharing, and co-development. Siemens' solar business, from 1996-2000, formed a joint venture with Shell and E.On, later acquired by Shell in 2001, expanding operations globally (Beise-Zee, 2004).

From multi-level perspective, this period also witnessed tensions between technology niche and industry regime, with lobbying reflecting struggles against competing technologies and vested interests, leading to closures and divestments by oil firms in the solar industry. Conversely, major solar cell manufacturers lobbied for solar panels, demonstrating the industry's response to negative lobbying.

***Table 3: IP sharing models in diffusion of solar PV* (1995- late 2010s)**

Levels	Actors	IP sharing models	Examples
New industry Association & new regime **US:** Direct subsidies (tax credits, preferential loans, cash rebates) **Japan**: Direct funding from electricity surcharge **Germany:** The Renewable Energy Sources Act, 2000 **China**: Solar Roof Program and Golden Roof Demonstration program in 2011	Large and small solar firms, private research institute and labs, government, and industry association	Semi-open IP model, e.g. informal IP & know-how transfer, non-exclusive in- & out-licensing, royalty free-non-exclusive licensing	From 1995-2006, informal IP exchange between US, German, and Japanese firms improved solar PV efficiency by 20% and reduced production cost In 2006, the Midwest Research Institute (MRI non-exclusively license its solar technologies to Ascent Solar Technologies, Inc. for th benefit of the public.

4.4. *Institutionalization of solar PV technology (late 2010s onwards)*

Since 2010, global innovations and diffusion of solar PV technology have surged, driven by collaborative efforts among industry associations like Japan Solar PV Energy Association, Solar Energy Industry Association (US), and European Photovoltaic Industry Association (France) (WIPO, 2020). These associations are actively engaged in trade, education, advocacy, and research, facilitating knowledge exchange and technology transfers among industry players.

Governments, firms, and associations engage in partnerships for PV technology development and dissemination, exemplified by NREL's National Center of Photovoltaic (NCPV). We observe the adoption of **semi-open IP model by** STS actors (such as firms and government agencies across countries), employing IP sharing mechanisms, including cross-licensing, non-exclusive, royalty-free licensing, technology consortium for the improvement of solar PV efficiency and cost reduction (See Table 4). Additionally, open IP models gain support, with initiatives like NREL's development of open-source software (SolarPILOT, SolTrace, and System Advisor Model) for industry and academia.

Table 4 IP sharing models for the institutionalization of renewables

IP sharing models for the institutionalization of renewables (late 2010s onwards)			
Levels	**Actors**	**IP sharing models**	**Examples**
New industry Association & new regime	Large and small solar firms, private research institute and labs, government, and industry association	Semi-open IP model, e.g. exclusive and non-exclusive in- & out-licensing, royalty free-non-exclusive licensing, Cross-licensing, R&D partnerships, IP sharing among consortium	• In 2011, Q-Cells SE obtained a non-exclusive license for efficient solar module technology from Kaneka Corporation. • In 2014, SunEdison Semiconductor Ltd secured a perpetual, royalty-free, non-exclusive license from SunEdicon Inc. for semiconductor solar technology. • In 2013, SunEdison and Soitec engaged in a patent cross-licensing and R&D agreement for supply-chain and ecosystem building for silicon-on-insulator wafer products. • In 2020, SunPower Corporation and Maxeon Solar Pte. Ltd entered a cross-licensing pact. • In 2018, SolarWindow Technologies, Inc, partnered with US DOE, ANL, and NREL forming Cooperative Research and Development Agreement (CRADA) • In 2020, a consortium of six solar companies, including Sunseap Group, collaborated on solar technology development in Singapore and Indonesia.

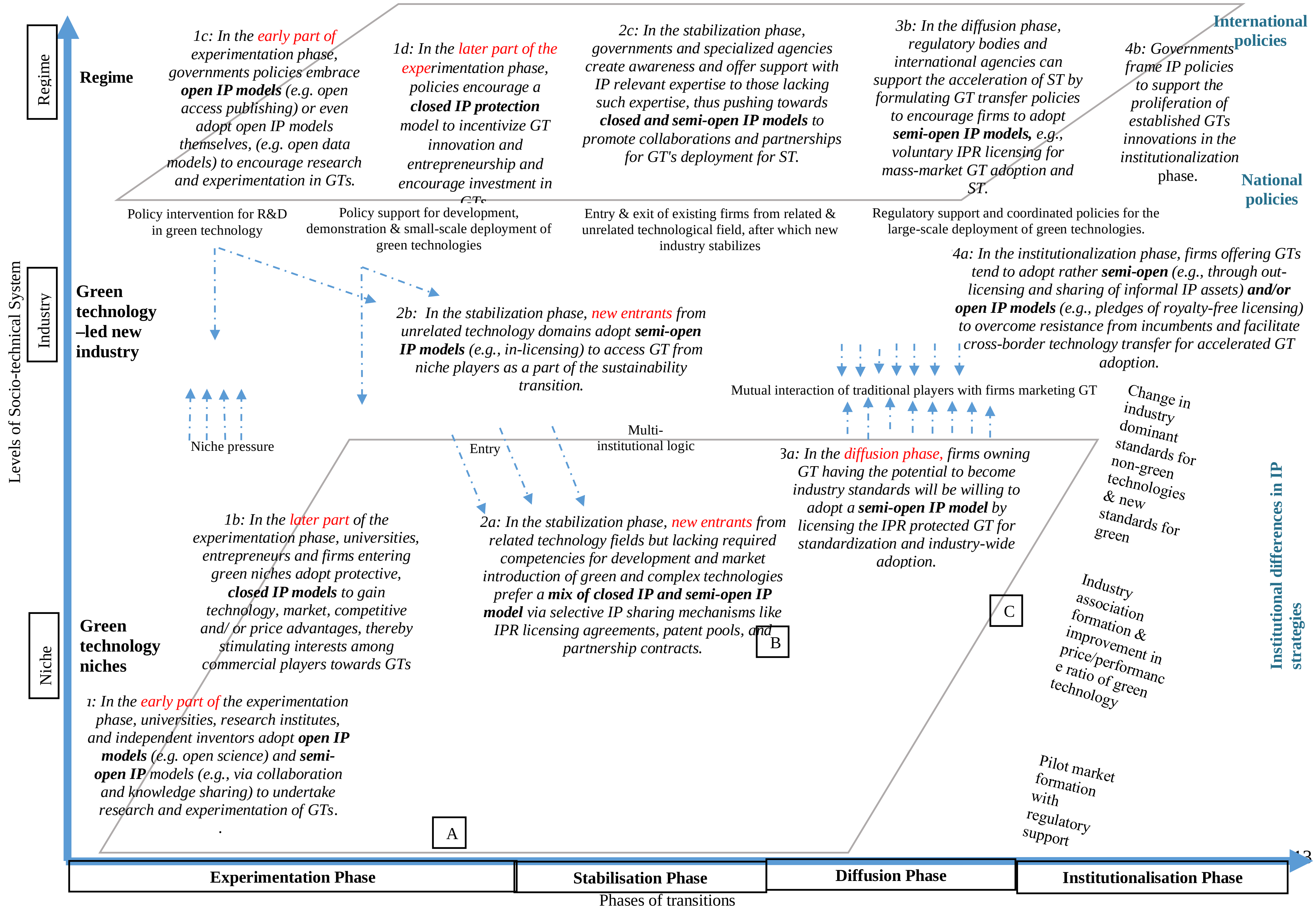
5. Propositions for the use of IP models at different levels and phases in sustainability transitions

In this section, we synthesize findings from the case study in section 4, illustrating how actors in the sustainability transition system use IP models and sharing mechanisms at niche and regime levels during the four ST phases as depicted in the MLP framework (See F**igure 2 and Table 5).** Building on historical cases, we enhance generalizability by incorporating additional examples.

Table 5: Conceptual integration of MLP framework and IP models' propositions for sustainability transition

Sustainability Transition Phase	**Socio-technical System levels**	**IP sharing mechanisms**	**IP** models **propositions**
Experimentation: ● Pre-competitive, non-commercial research ● Entrepreneurial spin-offs from universities, research institutions and private R&D labs	**Niche** ● Inventors need freedom to operate for experiments, fostering start-ups and spin-offs. **Regime** ● Limited regulatory intervention: niche experimentations receive limited R&D funding	**IP as a collaborative instrument** ● Publications and research collaborations facilitate IP sharing among patent owners and third parties, enhancing collective knowledge. **IP protection as an incentive to innovate.** ● IP protection fosters sustainable technology niches, prevents duplication, and provides freedom to operation. **IP as policy instrument** ● IP protection for private players aids knowledge-building and sets the stage for green technology experimentation. ● Regulators endorse open IP for data access, open-source publishing, and data sharing, promoting innovation	1a 1b 1c & 1d
Stabilization: ● Mutual interaction between firms, industry associations, and engineering communities ● Emergence of dominant design	**Niche (pilot) market** ● Firms, new and existing, enter the niche green technology development. **Landscape** ● Pressure on conventional regime. **Regime** ● Niche policies support demo projects, creating a pilot market	**IP for collaborative knowledge access** ● IP sharing and collaboration enable access to external expertise, accelerating development, and enhancing the performance of green technologies. **IP as a policy instrument for** GT **applications.** ● Regulatory bodies organize IP awareness programs, support IP protection, and facilitate transfer contributing to an effective innovation system for GT	2a & 2b 2c
Diffusion: ● Process and product improvement, product standardization, cost reduction, ● Competition, network externality, lobbying	**Partial regime replacement, green tech industry association and network formation** ● Growth and mass market formation for green technologies.	**IP for breakthroughs and mass markets:** ● IP sharing is crucial for breakthrough into mass markets, and open patent pools assist in navigating patent complexities. **IP as a policy tool for GT diffusion.** ● Encouraging GT transfer through semi-open IP models, such as voluntary IPR licensing, supports diffusion.	3a 3b
Institutionalization ● Anchoring of sustainable innovations in user behavior, policy regulations & industry	**Shifts from conventional regime to new green innovation regime.** ● National and international bodies implement new policies, replacing dominant designs, norms, and regulations.	**IP as a policy tool for** sustainable **technology innovations.** ● Broad exemptions from patent infringement for research using green patented technology and IP trading exchanges promote follow-on inventions in the technological field	4a & 4b

Figure 2: ***Integration of IP sharing models in the MLP framework***; Source: Developed by Authors



5.1. IP models in the Experimentation Phase

Niche level
In the early stages of the experimentation phase within the ST process**,** universities and research institutions exhibit a preference for high **openness.** This openness is evident in activities such as collaborative research and publishing, aligning with the **increasing prominence of open access**. The initial phase mirrors the 'science-dominated' period of technology-intensive industry emergence, defined as *"activities that establish the supporting scientific phenomena [..]"* ((Phaal et al., 2011) p. 221). However, as the experimentation progresses, factors like technological uncertainty, high R&D cost, and low demand prompt a shift towards exclusivity. In this later stage, **closed patent- or trade secret-based IP models become preferable,** resembling the 'technology-dominated' phase of industry emergence, defined as *"demonstrating the feasibility of a scientific phenomenon [..], to be integrated into an application-specific functional technology system."* (Phaal et al., 2011, p. 221). S**emi-open IP models comes to play to** facilitate commercial technology transfer, often through research partnerships from universities to commercial firms (Siegel et al., 2003).

Patent ownership and protection strategies
The ownership of patents provides non-commercial entities, such as universities, the flexibility to negotiate licensing agreements with commercial partners. A protective approach through closed IP models aids in advancing inventions towards industrial application, especially in the face of the double externality and market imperfections that encourage firms to extend their monopoly to recoup R&D costs (Png, 2017).

The benefits of patenting in the later part of the experimentation phase vary across technology fields. Inventors may file broad patents in fields like nanotechnology and geoengineering with broad potential uses to secure a competitive advantage (Chavez, 2015). Conversely, in areas like renewable energy with substitutes and expired base patents, patents for minor improvements become crucial to tackling competition (Barton et al., 2007). For small firms, invention protection and exclusive licensing become tools to attract venture capital funds and incumbents, facilitating the advancement of inventions by prototyping core or complementary technology (Tietze et al., 2017). Hence, we propose,

Proposition 1a*: In the early part of the experimentation phase, universities, research institutes, and independent inventors adopt open IP models (e.g. open science) and semi-open IP models (e.g., via collaboration and knowledge sharing) to undertake research and experimentation of green technologies.*

Proposition 1b: *In the later part of the experimentation phase, universities, entrepreneurs, and firms entering niches can adopt closed IP models to start initiating new niches and attract interest amongst commercial firms.*

Regulations at the regime level
During the early experimentation phase, Intellectual Property Rights (IPR) and innovation regulations become crucial. Policies promoting GT experimentation may include support withdrawal from less desirable conventional technologies, encouraging R&D investment, collaborative research, and openness in IP sharing. An example is the open data policy adopted by Transport for London in the UK, sharing real-time transport data to encourage GT innovations in the mobility sector (Hogge, n.d.).

In the technology-dominated part of experimentation, provision for the formal IP protection (except trade-secrets) provisions become vital to attract investments, prevent duplication of efforts, and ensure freedom to operate. Government initiatives such as the "Green IP Scheme" or Patent Insurance Scheme, launched in the US in 2008, show the commitment to finance R&D investment through IP premiums charged from all patent applicants/owners. Fast-track patent examination processes for green patent applications in various countries further exemplify the effort to promote green technologies (Lane, 2012). The Green Technology Pilot Program started in the US in 2009 to fast-track examination of green patent applications led to a substantial increase in patent filings. Thus, we propose,

Proposition 1c: *In the early part of the experimentation phase, governmental policies might embrace open IP models (e.g. open access publishing) or even adopt open IP models themselves, (e.g. open data models) to encourage research and experimentation in green technologies.*

Proposition 1d*: In the later part of the experimentation phase, government policies can encourage closed IP protection models to incentivize innovation and entrepreneurship and attract investment in technologies.*

5.2. IP models in the Stabilization Phase

Niche pilot market

The stabilization phase witnesses the entry of firms from various technology fields into the emerging green industry. Established firms from related fields are likely to have the absorptive capacity but may lack competencies to develop the emerging technology in-house. They, therefore, enter using a combination of **closed and semi-open IP models**, leveraging internal R&D, and acquiring external IP, and through exclusive in-licensing of the patents from originators. The diversification of BASF into the emerging European fuel-cell industry during the early 2000s represents one such example. BASF adopted a closed IP model, filing patent applications for in-house inventions, establishing the research centre for prototype demonstration and testing. Additionally, it embraced semi-open IP model by acquiring Pemeas Fuel Cell Technologies in 2006 (Tanner, 2014). Firms may also adopt multi-actor semi-open IP models like patent pools, product development partnerships, and public-private partnerships. Patent pools involving independent licensing options are likely to enable a reduction of technology prices (Boutin, 2016).

Proposition 2a*: In the stabilization phase, new entrants from related technology fields that lack required technical know-how about the emerging technology enter the emerging industry by adopting a mix of closed IP and semi-open IP models using, e.g. selective IP licensing agreements, patent pools, and partnership contracts.*

New entrants from unrelated technology fields adopt semi-open IP models, involving patent licensing and know-how sharing to access external, complementary expertise for technology development (Jacobsson and Bergek, 2011). Collaboration mechanisms such as joint ventures and product development partnerships become prevalent, aiming to reduce transaction costs in entering non-core green areas. Cross-industry product development partnership' where firms co-own IP assets, forms another common approach adopted in this stage. For instance, in 2006, a large multinational chemical manufacturing firm in India entered a product development partnership with firms in the consumer goods industry to develop and commercialize rice-husk based low-cost water purifiers. The firm also co-owned IP with automobile firms to manufacture material for green tyres. If applied during the industry emergence, inter-sectoral, cross-industry knowledge sharing can trigger STs.,

Proposition 2b*: In the stabilization phase, new entrants from unrelated technology domains adopt semi-open IP models (e.g., in-licensing) to access green technologies from niche players as a part of the sustainability transition.*

Government Initiatives in the Stabilization Phase

Governments and specialized agencies play a crucial role in creating awareness and providing support with IP-related expertise. Initiatives such as WIPO Green, an online GT market platform, leverage semi-open IP models like patent pools to encourage collaboration and voluntary IP sharing. Specialized networks, like India's Gujarat Grassroots Innovation Augmentation Network, aim to create IP awareness among grassroots innovators and assist them in IP protection and technology licensing (Ustyuzhantseva, 2015).

Proposition 2c*: In the stabilization phase, governments and specialized agencies create awareness and offer support with IP relevant expertise to those (new SMEs) lacking such expertise, thus pushing towards closed and semi-open IP models to promote collaborations and partnerships for green technology's deployment for sustainability transitions.*

5.3. IP models in the Diffusion Phase

New industry association and network formation

The diffusion phase involves market creation, competition and lobbying from conventional technology players. Accordingly, it is in this phase where it is likely that IP-related tensions arise at the firm and policy levels.

Hence institutional support becomes crucial to ensure IP facilitates, rather than hinders, mass-market diffusion. At this stage, closed IP models are likely to block collaboration and limit the widespread diffusion of GTs. Firms with proprietary GTs may shift from closed to open IP models (either voluntarily or pushed to) to accelerate technology diffusion. Coca-Cola's IP model for the plant-based bottle material developed in 2009 exemplify this shift from initially being closed and internal usage to gradually opening up the IP to incumbents in other industries, such as the automobile industry, and eventually, in 2019, to everyone, including competitors, across multiple industries ("Why we're sharing our PlantBottle technology with the world," n.d.).

Standard-setting organizations contribute to the development of new technology standards, aiding in technology diffusion. Firms might adopt semi-open IP models by licensing IPR-protected GTs for standardization and industry-wide adoption (Pisano and Teece, 2007). Where technological use requires a complete ecosystem formation, firms may share informal IP assets such as technological know-how, confidential information, and design knowledge (Hall et al., 2014), rather than just sharing formal IP assets. An illustration of this is an Indian electric scooter maker that initially employed a closed IP model but later shifted to a semi-open IP model. They opened sub-systems, control, designs, and dimensions to standard-setting organizations, fostering new player entry and ecosystem development around the technology.

Green firms often enter international markets in this phase through IP sharing via licensing agreements, joint ventures, and partnerships, providing exclusivity in target countries. For instance, in 2010, eSolar, a startup, signed the largest-ever master licensing agreement, exclusively licensing IP-protected technology to Pengali, a Chinese electric company, for constructing solar thermal power plants in China (Lane, 2009), showcasing the preference for patent licensing and standard setting for mass-market formation and widespread diffusion. Hence, we propose,

Proposition 3a: *In the diffusion phase, firms owning green technologies having the potential to become industry standards will be willing to adopt a semi-open IP model by licensing the IPR protected green technology for standardization and industry-wide adoption.*

Partial regime replacement

Policy initiatives, exemplified by the UNFCCC's Technology Mechanism and Clean Development Mechanism, aim to facilitate international technology transfer for emission reduction in developing countries. However, attempts to formulate IPR policies, whether biased towards closed or open IP models, create tensions between countries with different IP regimes, hindering consensus (Lane, 2009). Broader technology transfer policies, allowing firms to voluntarily determine IP licensing and transfer terms, prove more advantageous (Lane, 2009). Critical for cost reduction in Green Technologies (GTs), standardization efforts, such as those by Russia's Technical Committee of Standardization No. 366, promote resource-efficient designs (Benuzh and Orenburova, 2016). These policies may require IP sharing among relevant actors nationally and internationally. Hence, we propose,

Proposition 3b*: In the diffusion phase, regulatory bodies and international agencies can support the acceleration of sustainability transition by formulating green technology transfer policies to encourage firms to adopt semi-open IP models, e.g., voluntary IPR licensing for mass-market green technology adoption and sustainability transition.*

5.4. IP models in the Institutionalization phase

Shifts from conventional regime to new green innovation regime.

IPR policies on exchange and collaboration, coupled with policies such as subsidies, carbon trading, taxes encourage industry investment in climate technology (Reichman et al., 2014; Raiser et al., 2017). The establishment of IP trading exchanges (Intellectual Property Exchange International, IPXI) supports development and diffusion of technologies. Policy tools such as compulsory licensing with broad exemptions from patent infringement help disseminating and follow-on development of technology when the market fails (Chavez, 2015), e.g., in the agriculture and generic medicines sectors (Reynolds et al., 2017).

Firms also adopt open IP models such as royalty-based or royalty-free licensing, pledges, open patent pools, and data sharing or research commons. In 2008, the Eco-Patent commons initiative, involving IBM, Nokia, Sony, and Pitney Bowes, exemplified an open patent pool pledging green patents (Contreras et al., 2018). Conversely, the 2010 GreenXchange initiative by Nike and others, a closed patent pool, proved more effective. Under this initiative, registered firms could pledge patents, charge fees, and selectively deny usage (Hall and Helmers, 2013). Thus:

Proposition 4a*: In the diffusion phase, firms offering green technologies tend to adopt rather semi-open (e.g., through out-licensing and sharing of informal IP assets) and/or open IP models (e.g., pledges of royalty-free licensing) to overcome resistance from incumbents and facilitate cross-border technology transfer for accelerated green technology adoption.*

Proposition 4b: *Governments frame IP policies to support the proliferation of established green technologies and subsequent innovations in the institutionalization phase.*

6. Discussion: Limitations and future research

Our paper explores the role of IP models across various actors during the phases of STs, Addressing a notable gap in existing literature. Grounded in Geels' MLP framework (2011a) and Vimalnath et al.'s (2017) IP model typology, we propose and illustrate, via solar PV case study, the collaborative nature of IP models and their potential as a policy tool in advancing STs. This conceptualization elucidates the dynamics of relevant actors' IP models at the niche and regime levels during the ST process.

The propositions underscore mitigating uncertainties in experimentation using a closed IP model, benefiting individuals, institutions, or small firms experimenting with new technologies (Tietze et al., 2017; Sodhi et al., 2019). In the stabilization phase, a blend of closed and semi-open IP models proves effective, spreading risks across multiple stakeholders through broader co-creation (Eppinger et al., 2021; Jain and Gurtoo, 2021). Meanwhile, the diffusion and institutionalization phases benefit from combining semi-open and fully open IP models, adopting partial or complete openness in IP sharing (Shapiro, 2000). In the final stage, we propose IPR policies with effective governance mechanisms playing a role in channeling transition towards sustainability.

The current framework demonstrates a relatively long time-to-market for GTs compared to conventional technology, owing to the peculiar characteristics of the former. Thus, we present the following policy implications: Firstly, we advocate for a subscription-based IP trading platform (with subsidized fees for small firms) facilitating partner searches, preventing imitation, and reducing search costs for GT transactions. Large firms with market access and capital for technology development can have early access to GT, reducing the risk of imitation.

Secondly, provisions for informal IP transfer can encourage the sharing of soft or non-patentable elements, fostering technological know-how exchange. Mere ownership of patents or their transfer may not work as efficiently until the firms exchange the technology's soft elements through know-how transfer. Examples and case evidence show that trading of patented technology, co-development partnerships and know-how exchange led to technology improvement, design efficiency, and crystalline silicon technology cost reduction. Thirdly, public measures, such as public procurement, tax credits, and R&D subsidies, can reduce uncertainty and promote R&D investment and demand for green products. Public authorities can provide incentives, grants, or awards to companies to encourage informal and formal IP assets' exchange or sharing between companies. Lastly, access to open-source software for innovative green technologies is proposed to facilitate development, efficiency improvement, and technology diffusion.

From a managerial perspective, our propositions emphasize the pivotal role of IP models as drivers in facilitating STs. IP protection offers owners the control and flexibility to decide and negotiate IP sharing terms in joint developments and commercial partnerships. Such collaborations are essential for green technologies, given their complexity and cumulative nature. *Second,* the propositions offer guidance on when actors can opt for closed, semi-open or fully open-IP models during transitions phases. This strategic sequencing allows organizations to contribute to ST without compromising profits. The study advocates for knowledge sharing through open science models in the experimentation phase and demonstrates that closed IP models attract investments and partnerships upon successful prototyping, enabling accelerated adoption and diffusion through licensing.

7. Conclusion

In conclusion, this study addresses the critical gap in understanding how Intellectual Property (IP) functions within the broader dynamics of Sustainability Transitions (ST), particularly in the context of Green Technologies (GTs). Leveraging Geels' Multi-Level Perspective (MLP) model, we explored how actors within Socio-Technical Systems utilize various IP models for the development and diffusion of GTs. The propositions derived from our analysis underscore the importance of adopting specific IP models at different phases of the ST process. The findings provide valuable insights for policymakers and organizations, emphasizing the need for nuanced IP strategies to foster innovation, mitigate risks, and accelerate the adoption of GTs in pursuit of sustainable development goals.

The study has certain limitations, as it doesn't compare IP models for GTs with varying characteristics, such as design complexity and capital requirements. For instance, biomass power and carbon capture technologies differ significantly from solar PVs and LEDs. (Malhotra and Schmidt, 2020). The study does not provide specific outcomes generated by adopting a particular IP model for a particular GT. It also doesn't assess the effectiveness of policy mixes across different transition stages or quantify the necessary degree of openness for GT diffusion. Future research should address these gaps, exploring differences in IP models based on GT characteristics, understanding the effectiveness of open IP models during diffusion, and identifying optimal regulatory instruments for GT creation and diffusion.

REFERENCES

Baker, S., Mezzetti, C., 2005. Disclosure as a Strategy in the Patent Race. The Journal of Law and Economics 48, 173–194. https://doi.org/10.1086/426879

Barton, John H., Director, P., Bellmann, C., Vivas, D., Gueye, M.K., 2007. Intellectual Property and Access to Clean Energy Technologies in Developing Countries: An Analysis of Solar Photovoltaic. Biofuel and Wind Technologies. Issue Paper No.

Beise-Zee, R., 2004. The International Adoption of Photovoltaic Energy Conversion Is Japan a Lead Market?

Benuzh, A., Orenburova, E., 2016. Standardization of green building technologies for environment design. MATEC Web Conf. 86, 05014. https://doi.org/10.1051/matecconf/20168605014

Beyer, P., 2013. Developing socially responsible intellectual property licensing policies: Non-exclusive licensing initiatives in the pharmaceutical sector, in: Research Handbook On Intellectual Property Licensing. pp. 227–256. https://doi.org/10.4337/9781781005989.00018

Boutin, A., 2016. Screening for Good Patent Pools through Price Caps on Individual Licenses. American Economic Journal: Microeconomics 8, 64–94. https://doi.org/10.1257/mic.20140237

Chavez, A.E., 2015. Exclusive Rights to Saving the Planet: The Parenting of Geoengineering Inventions. Nw. J. Tech. & Intell. Prop. 13, 1.

Chesbrough, H., 2003. The logic of open innovation: managing intellectual property. California management review 33–58.

Contreras, J.L., Eisen, M., Ganz, A., Lemley, M., Molloy, J., Peters, D.M., Tietze, F., 2020. Pledging intellectual property for COVID-19. Nat Biotechnol 38, 1146–1149. https://doi.org/10.1038/s41587-020-0682-1

Contreras, J.L., Hall, B.H., Helmers, C., 2019. Pledging Patents for the Public Good: Rise and Fall of the Eco-Patent Commons. Hous. L. Rev. 57, 61.

Ehrnsperger, J.F., Tietze, F., 2019. IP pledges, open IP or patent pools? Developing taxonomies in the thicket of terminologies.

Eisenhardt, K.M., 1989. Building Theories from Case Study Research. AMR 14, 532–550. https://doi.org/10.5465/amr.1989.4308385

Eppinger, E., 2015. Patentpools: Eigenschaften, Motive und Implikationen. Springer-Verlag.

Eppinger, E., Jain, A., Vimalnath, P., Gurtoo, A., Tietze, F., Hernandez Chea, R., 2021. Sustainability transitions in manufacturing: the role of intellectual property. Current Opinion in Environmental Sustainability 49, 118–126. https://doi.org/10.1016/j.cosust.2021.03.018
Farla, J., Markard, J., Raven, R., Coenen, L., 2012. Sustainability transitions in the making: A closer look at actors, strategies and resources. Technological Forecasting and Social Change 79, 991–998. https://doi.org/10.1016/j.techfore.2012.02.001
Gales, B., Kander, A., Malanima, P., Rubio, M., 2007. North versus South: Energy transition and energy intensity in Europe over 200 years. European Review of Economic History 11, 219–253. https://doi.org/10.1017/S1361491607001967
Geels, F., 2005. Co-evolution of technology and society: The transition in water supply and personal hygiene in the Netherlands (1850–1930)—a case study in multi-level perspective. Technology in Society 27, 363–397. https://doi.org/10.1016/j.techsoc.2005.04.008
Geels, F.W., 2019. Socio-technical transitions to sustainability: a review of criticisms and elaborations of the Multi-Level Perspective. Current Opinion in Environmental Sustainability, Open Issue 2019 39, 187–201. https://doi.org/10.1016/j.cosust.2019.06.009
Geels, F.W., 2011. The multi-level perspective on sustainability transitions: Responses to seven criticisms. Environmental Innovation and Societal Transitions 1, 24–40. https://doi.org/10.1016/j.eist.2011.02.002
Geels, F.W., 2006a. The hygienic transition from cesspools to sewer systems (1840–1930): The dynamics of regime transformation. Research Policy 35, 1069–1082. https://doi.org/10.1016/j.respol.2006.06.001
Geels, F.W., 2006b. Major system change through stepwise reconfiguration: A multi-level analysis of the transformation of American factory production (1850–1930). Technology in Society 28, 445–476. https://doi.org/10.1016/j.techsoc.2006.09.006
Geels, F.W., 2005. The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930). Technology Analysis & Strategic Management 17, 445–476. https://doi.org/10.1080/09537320500357319
Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. Research Policy 33, 897–920. https://doi.org/10.1016/j.respol.2004.01.015
Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Research Policy, NELSON + WINTER + 20 31, 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8
Geels, F.W., Schot, J., 2007. Typology of sociotechnical transition pathways. Research Policy 36, 399–417. https://doi.org/10.1016/j.respol.2007.01.003
Geels, F.W., Sovacool, B.K., Schwanen, T., Sorrell, S., 2017. The Socio-Technical Dynamics of Low-Carbon Transitions. Joule 1, 463–479. https://doi.org/10.1016/j.joule.2017.09.018
Gerring, J., 2004. What Is a Case Study and What Is It Good for? American Political Science Review 98, 341–354. https://doi.org/10.1017/S0003055404001182
Ghisetti, C., Marzucchi, A., Montresor, S., 2015. The open eco-innovation mode. An empirical investigation of eleven European countries. Research Policy 44, 1080–1093. https://doi.org/10.1016/j.respol.2014.12.001
Haegel, N.M., Kurtz, S.R., 2021. Global Progress Toward Renewable Electricity: Tracking the Role of Solar. IEEE Journal of Photovoltaics 11, 1335–1342. https://doi.org/10.1109/JPHOTOV.2021.3104149
Hall, B., Helmers, C., Rogers, M., Sena, V., 2014. The Choice between Formal and Informal Intellectual Property: A Review. Journal of Economic Literature 52, 375–423. https://doi.org/10.1257/jel.52.2.375
Hall, B.H., Helmers, C., 2013. Innovation and diffusion of clean/green technology: Can patent commons help? Journal of Environmental Economics and Management 66, 33–51. https://doi.org/10.1016/j.jeem.2012.12.008
Henkel, J., 2006. Selective revealing in open innovation processes: The case of embedded Linux. Research Policy 35, 953–969. https://doi.org/10.1016/j.respol.2006.04.010
Hernandez Chea, R., Jain, A., Bocken, N., 2020. A Conceptualization of Firm Activities Toward Sustainability Transitions. Academy of Management Annual Meeting Proceedings 2020, 1–1.
Hogge, B., n.d. TRANSPORT FOR LONDON GET SET, GO! OPEN DATA 15.

Horbach, J., Oltra, V., Belin, J., 2013. Determinants and Specificities of Eco-Innovations Compared to Other Innovations—An Econometric Analysis for the French and German Industry Based on the Community Innovation Survey. Industry and Innovation 20, 523–543. https://doi.org/10.1080/13662716.2013.833375
How the solar cell found the spotlight, 2019. . Energy dialogue - the Axpo Magazine.
Jacobsson, S., Bergek, A., 2011. Innovation system analyses and sustainability transitions: Contributions and suggestions for research. Environmental Innovation and Societal Transitions 1, 41–57. https://doi.org/10.1016/j.eist.2011.04.006
Jain, A., Gurtoo, A., 2021. Can the restrictive boundaries of intellectual property create a larger social impact? CURRENT SCIENCE 120, 3.
Jones, G., Bouamane, L., 2012. "Power from Sunshine": A Business History of Solar Energy 88.
Kemp, R., 1994. Technology and the transition to environmental sustainability. Futures 26, 1023–1046. https://doi.org/10.1016/0016-3287(94)90071-X
Kemp, R., Schot, J., Hoogma, R., 1998. Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. Technology Analysis & Strategic Management 10, 175–198. https://doi.org/10.1080/09537329808524310
Kieff, F.S., 2005. IP Transactions: On the Theory & Practice of Commercializing Innovation. SSRN Journal. https://doi.org/10.2139/ssrn.821327
Kim, B., 2003. Managing the transition of technology life cycle. Technovation 23, 371–381. https://doi.org/10.1016/S0166-4972(02)00168-2
Klingenberg, B., Watson, K., 2010. Intellectual Property Exchange Between Two Partner Companies-Application of the Theory of Constraints Thinking Processes. Journal of Business and Management 16, 102.
Köhler, J., Geels, F.W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M.S., Nykvist, B., Pel, B., Raven, R., Rohracher, H., Sandén, B., Schot, J., Sovacool, B., Turnheim, B., Welch, D., Wells, P., 2019. An agenda for sustainability transitions research: State of the art and future directions. Environmental Innovation and Societal Transitions 31, 1–32. https://doi.org/10.1016/j.eist.2019.01.004
Kotchen, M.J., 2005. Impure public goods and the comparative statics of environmentally friendly consumption. Journal of Environmental Economics and Management 49, 281–300. https://doi.org/10.1016/j.jeem.2004.05.003
Kumar, K., 2020. A History of the Solar Cell, in Patents. Intellectual Property Magazine.
Lane, E., 2009. Clean Tech Reality Check: Nine International Green Technology Transfer Deals Unhindered by Intellectual Property Rights. Santa Clara Computer & High Tech. L.J. 26, 533.
Lane, E.L., 2012. Building the Global Green Patent Highway: A Proposal for International Harmonization of Green Technology Fast Track Programs. Berkeley Technology Law Journal 27, 1119–1170.
Laukkanen, M., Patala, S., 2014. ANALYSING BARRIERS TO SUSTAINABLE BUSINESS MODEL INNOVATIONS: INNOVATION SYSTEMS APPROACH. Int. J. Innov. Mgt. 18, 1440010. https://doi.org/10.1142/S1363919614400106
Lee, D., Hess, D.J., 2019. Incumbent resistance and the solar transition: Changing opportunity structures and framing strategies. Environmental Innovation and Societal Transitions 33, 183–195. https://doi.org/10.1016/j.eist.2019.05.005
Lema, R., Lema, A., 2012. Technology transfer? The rise of China and India in green technology sectors. Innovation and Development 2, 23–44. https://doi.org/10.1080/2157930X.2012.667206
Liddicoat, J., 2017. Standing on the Edge – What Type of "Exclusive Licensees" Should be Able to Initiate Patent Infringement Actions? IIC International Review of Intellectual Property and Competition Law 48, 626–651. https://doi.org/10.1007/s40319-017-0620-z
Loorbach, D., 2010. Transition Management for Sustainable Development: A Prescriptive, Complexity-Based Governance Framework. Governance 23, 161–183. https://doi.org/10.1111/j.1468-0491.2009.01471.x
Malhotra, A., Schmidt, T., 2020. Accelerating Low-Carbon Innovation. Joule 4, 1–9. https://doi.org/10.1016/j.joule.2020.09.004
Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: An emerging field of research and its prospects. Research Policy, Special Section on Sustainability Transitions 41, 955–967.

https://doi.org/10.1016/j.respol.2012.02.013
Markard, J., Truffer, B., 2008. Actor-oriented analysis of innovation systems: exploring micro–meso level linkages in the case of stationary fuel cells. Technology Analysis & Strategic Management 20, 443–464. https://doi.org/10.1080/09537320802141429
Moreno, M., Court, R., Wright, M., Charnley, F., 2019. Opportunities for redistributed manufacturing and digital intelligence as enablers of a circular economy. International Journal of Sustainable Engineering 12, 77–94. https://doi.org/10.1080/19397038.2018.1508316
Nemet, G.F., 2019. How Solar Energy Became Cheap: A Model for Low-Carbon Innovation, 1st ed. Routledge Taylor and Francis Group.
Phaal, R., O'Sullivan, E., Routley, M., Ford, S., Probert, D., 2011. A framework for mapping industrial emergence. Technological Forecasting and Social Change, Using Technological Intelligence for Strategic Decision Making in High Technology Environments 78, 217–230. https://doi.org/10.1016/j.techfore.2010.06.018
Pisano, G.P., Teece, D.J., 2007. How to Capture Value from Innovation: Shaping Intellectual Property and Industry Architecture. California Management Review 50, 278–296. https://doi.org/10.2307/41166428
Plooy, P.D., 2013. Technology Diffusion through Intellectual Property Rights: Innovating to Combat Climate Change [WWW Document]. Africa Portal. URL https://www.africaportal.org/publications/technology-diffusion-through-intellectual-property-rights-innovating-to-combat-climate-change/ (accessed 6.17.21).
Png, I.P.L., 2017. Law and Innovation: Evidence from State Trade Secrets Laws. The Review of Economics and Statistics 99, 167–179. https://doi.org/10.1162/REST_a_00532
Raiser, K., Naims, H., Bruhn, T., 2017. Corporatization of the climate? Innovation, intellectual property rights, and patents for climate change mitigation. Energy Research & Social Science 27, 1–8. https://doi.org/10.1016/j.erss.2017.01.020
Rennings, K., 2000. Redefining innovation — eco-innovation research and the contribution from ecological economics. Ecological Economics 32, 319–332. https://doi.org/10.1016/S0921-8009(99)00112-3
Reynolds, J.L., Contreras, J.L., Sarnoff, J.D., 2018. Intellectual property policies for solar geoengineering. Wiley Interdiscip. Rev.-Clim. Chang. 9, e512. https://doi.org/10.1002/wcc.512
Rosenbloom, R.S., 2000. Leadership, Capabilities, and Technological Change: The Transformation of NCR in the Electronic Era. Strategic Management Journal 21, 1083–1103. https://doi.org/10.1002/1097-0266(200010/11)21:10/11<1083::AID-SMJ127>3.0.CO;2-4
Sarnoff, J.D., 2013. Government Choices in Innovation Funding (With Reference to Climate Change) (SSRN Scholarly Paper No. ID 2372719). Social Science Research Network, Rochester, NY.
Siegel, D.S., Waldman, D.A., Atwater, L.E., Link, A.N., 2003. Commercial knowledge transfers from universities to firms: improving the effectiveness of university–industry collaboration. The Journal of High Technology Management Research 14, 111–133. https://doi.org/10.1016/S1047-8310(03)00007-5
Siltaloppi, J., Ballardini, R.M., 2023. Promoting systemic collaboration for sustainable innovation through intellectual property rights. Journal of Co-operative Organization and Management 11, 100200. https://doi.org/10.1016/j.jcom.2023.100200
Smulders, M.J.M., van de Wiel, C.C.M., Lotz, L.A.P., 2021. The Use of Intellectual Property Systems in Plant Breeding for Ensuring Deployment of Good Agricultural Practices. Agronomy 11, 1163. https://doi.org/10.3390/agronomy11061163
SPIE - The International Society for Optics and Photonics, 2013. David Carlson: Laser processing promises to boost PV efficiency. SPIE - The International Society for Optics and Photonics.
Sternkopf, J., Tietze, F., Eppinger, E., Vimalnath, P., 2016. Open IP strategies for enabling sustainability transitions (Working Paper). Centre for Technology Management, Institute for Manufacturing. https://doi.org/10.17863/CAM.7143
Suh, J.W., Sohn, S.Y., Lee, B.K., 2020. Patent clustering and network analyses to explore nuclear waste management technologies. Energy Policy 146, 111794. https://doi.org/10.1016/j.enpol.2020.111794
Sutton, R.I., Callahan, A.L., 1987. The Stigma of Bankruptcy: Spoiled Organizational Image and Its Management. AMJ 30, 405–436. https://doi.org/10.5465/256007
Tanner, A.N., 2014. Regional Branching Reconsidered: Emergence of the Fuel Cell Industry in European Regions. Economic Geography 90, 403–427. https://doi.org/10.1111/ecge.12055

Tietze, F., Eppinger, E., Sternkopf, J., Vimalnath, P., 2017. IP strategies for sustainability, in: 2017 IEEE Technology & Engineering Management Conference (TEMSCON). Presented at the 2017 IEEE Technology & Engineering Management Conference (TEMSCON), IEEE, Santa Clara, CA, USA, pp. 173–178. https://doi.org/10.1109/TEMSCON.2017.7998373

Turnheim, B., Asquith, M., Geels, F.W., 2020. Making sustainability transitions research policy-relevant: Challenges at the science-policy interface. Environmental Innovation and Societal Transitions 34, 116–120. https://doi.org/10.1016/j.eist.2019.12.009

Ustyuzhantseva, O.V., 2015. Institutionalization of grassroots innovation in India. Current Science 108, 1476–1482.

Verbong, G., Geels, F., 2007. The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004). Energy Policy 35, 1025–1037. https://doi.org/10.1016/j.enpol.2006.02.010

Vimalnath, P., Tietze, F., Eppinger, E., Sternkopf, J., 2020. Closed, Semi-Open, or Fully-Open? Towards an Intellectual Property Strategy Typology. Proceedings 2020, 22070. https://doi.org/10.5465/AMBPP.2020.22070abstract

Why we’re sharing our PlantBottle technology with the world [WWW Document], n.d. URL https://www.coca-cola.eu/news/supporting-environment/why-were-sharing-our-plantbottle-technology-with-the-world (accessed 7.11.21).

Wilkinson, S., Hojckova, K., Eon, C., Morrison, G.M., Sanden, B., 2020. Is peer-to-peer electricity trading empowering users? Evidence on motivations and roles in a prosumer business model trial in Australia. Energy Res. Soc. Sci. 66, 101500. https://doi.org/10.1016/j.erss.2020.101500

Yin, R.K., 1994. Discovering the Future of the Case Study. Method in Evaluation Research. Evaluation Practice 15, 283–290. https://doi.org/10.1177/109821409401500309

Ziegler, N., Gassmann, O., Friesike, S., 2014. Why do firms give away their patents for free? World Patent Information 37, 19–25.