Making Technological Innovation Work for Sustainable Development

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Abstract

Sustainable development requires harnessing technological innovation to improve human well-being in current and future generations. However, impoverished, marginalized, and unborn populations too often lack the economic and political power to shape innovation systems to meet their needs. Issues arise at all stages of innovation, from invention of a technology through its selection, production, adaptation, adoption, and retirement. We argue that three insights should inform efforts to intervene in innovation systems for sustainable development. First, innovation processes do not evolve linearly, but rather emerge from complex adaptive systems involving many actors and institutions operating simultaneously from local to global levels. Second, there has been significant experimentation in mobilizing technology for sustainable development in the health, energy, and agriculture sectors, among others, but learning from past experience requires structured cross-sectoral comparisons and recognition of the socio-technical nature of innovation systems. Third, the current constellation of rules, norms, and incentives shaping technological innovation is often not aligned towards sustainable development. Past experience demonstrates that it is possible to reform these institutions to re-orient innovation, and many actors have the power to do so through research, advocacy, training, convening, policymaking, and financing. We offer three proposals to begin: establishing channels for regularized learning across domains of practice, developing measures that systematically take into account the interests of underserved populations throughout the innovation process, and reforming institutions to re-orient innovation systems towards sustainable development in a manner that considers all innovation stages and decision-making levels at the outset.

Keywords: sustainable development, technology, innovation systems, complex adaptive systems, knowledge systems

Significance Statement

The 2015 Sustainable Development Goals and Paris Agreement on climate change heightened global attention on sustainable development. Transitioning toward sustainable development will require technological innovation in many areas, such as clean energy and water-saving agriculture. However, unless the rules and incentives shaping innovation systems change, this transition will be impossible. Barriers to overcome include inadequate investment in technologies that could help people living in poverty, a lack of affordable and suitable technologies to address a wide range of sustainable development goals, and overuse of technologies that place unfair burdens on future generations. In this paper, we identify the fundamental reasons why current innovation systems fall short, describe what needs to change, and offer several proposals to begin making such change.

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Technological innovation is at the heart of sustainable development. In September 2015, following an extensive multi-year negotiation among governments, 193 countries of the United Nations committed to 17 Sustainable Development Goals (SDGs). Innovation itself is one of the SDGs (Goal 9) and also a means to achieve the others.

Technology is the subset of knowledge that includes the full range of devices, methods, processes, and practices that can be used "to fulfill certain human purposes in a specifiable and reproducible way (1). Innovation is the "process by which technology is conceived, developed, codified, and deployed" (1). The innovation process occurs in multi-faceted "innovation systems" comprised of socially negotiated goals, the technologies needed to reach these goals, people and organizations, and the rules and incentives that shape their decisions (2, 3). Many studies of innovation have focused on specific nations (3), sectors (4), or technologies (5). However, learning across these approaches and experiences is less common.

Sustainable development requires simultaneously advancing inter- and intra-generational equity. However, innovation does not always advance equity. For example, global investment in research and development (R&D) in medicines for "neglected diseases" is inadequate because the developing country populations who bear the primary burden of such diseases lack the means to incentivize such investment (6). Even when innovation does advance equity, it may not do so for both current and future generations—rather, these goals may conflict (7). For example, current investment in low-carbon energy does not fully reflect the interests of future generations who will be impacted by climate change (8). These unborn populations cannot influence current innovation systems.

Making technologies work for sustainable development will require greater clarity in conceptualizing the innovation process itself, identifying barriers to innovation, and learning from a wealth of academic research and past experience. Innovation scholars have proposed several conceptual frameworks for understanding how technologies emerge, change, and are adopted (3, 4, 9, 10). Yet these literatures are not explicitly connected to the specific problems facing actors promoting sustainable development (e.g., scientists conducting early-stage research, donors selecting particular technologies for funding, or governments promoting technology cooperation (11)). In this paper, we link a wide range of scholarship to empirical cases and real-world implementation challenges to highlight ways of promoting technological innovation for sustainable development.

We present three insights: 1) innovation is a complex adaptive system with non-linearities and tipping points; 2) the socio-technical nature of innovation enables deeper understanding of barriers to innovation; and 3) the capacity of actors to promote innovation is restricted by institutions not oriented towards sustainable development, but reform is possible. To illustrate these insights, we use a common set of cases that concern physical artifacts and non-physical practices; technologies at different levels of maturity; a range of geographic areas; and interventions to address various sustainable development needs (this set of cases is presented in more detail in Table 1 and the Supporting Information).

1. Understanding Innovation as a Complex Adaptive System

An "innovation system" is the connected set of actors and institutions that shape the process of technological change. Understanding how innovation systems work requires analyzing the actors and institutions that contribute to innovation in a geographic region (3), sector (4), or technological area (9). Actors typically include individuals and organizations, public and private, operating at multiple scales (e.g., central governments, local authorities, universities, private firms, non-profits, and technology users). Institutions include the set of formal and informal rules, norms, decision-making procedures, beliefs, incentives and expectations that guide the interactions and behavior of actors in an innovation system (12–15). The connections of actors and institutions across the many stages of the innovation process, which occur in multiple sectors and at different decision-making levels, make innovation systems complex and adaptive.

1.1. Innovation Systems Operate at Multiple Stages, Sectors, and Levels

Innovation happens in multiple stages that are tightly linked, often overlap, and do not necessarily occur in a specific order. By "innovation stage" we refer to the variety of activities that occur during the innovation process to shape technological change. There are a number of different ways innovation systems and activities can be conceptualized (4, 9, 16). For clarity of exposition, we group different types of innovation activities into seven stages: invention (the process leading to the initial discovery of a technology), selection (the choice of a technology for a given setting), early adoption (the use of a selected technology in a specific context), production (the manufacturing of a technology), adaptation (efforts by users or inventors to modify a technology to better serve the needs of individual users), widespread use (the broad adoption of a technology in different communities of users), and retirement (the replacement of a technology by a new, more effective technology).

The types of activities that occur in different innovation stages often require distinct modes of thinking, the engagement of diverse actors (3), and the mobilization of many physical and intangible resources. Hence, the performance of this set of interconnected and non-linear innovation stages requires the broader system to perform specific "functions" (9). Further, innovation stages often occur simultaneously, involving multiple actors at different decision-making levels, from individuals to multinational governance bodies. Actors and their activities are embedded in social systems, which are governed by institutions that shape innovation processes (17). We return to this in Section 2, where we explore the interlinked socio-technical dimensions of innovation systems, and in Section 3, where we explore the reciprocal relationship between actors and institutions.

The range of actors, decision-making levels, and resources relevant to a single technology is illustrated by the case of artemisinin combination therapy (ACT) for malaria (Table 1). In the 1990s and 2000s, R&D for new drugs to replace those whose efficacy had been eroded by resistance was taking place in in China (in government-supported labs) and Switzerland (at a private firm), leading to the invention of ACTs. Following a proposal by a panel of US Institute of Medicine experts, the technology was subsidized by the Global Fund to Fight AIDS, Tuberculosis and Malaria and UNITAID to make these drugs more affordable in Southeast Asia and sub-Saharan Africa. Simultaneously, governments at the World Health Assembly were negotiating international norms to protect existing drugs from antimicrobial resistance.

Due to the pervasiveness of linkages in the innovation system across stages, sectors, and decision-making levels, intervening in any one part of an innovation system can create negative and positive externalities that act as "ripple effects" throughout the system. On the negative side, innovation can cause unintended consequences, particularly as technologies gain more widespread use, such as the impact of local incentives for biofuel development on global food prices (18). On the positive side, innovation in one technology area can lead to "spillovers" that enable more rapid improvements and new applications in other areas (19). In this sense, when new knowledge becomes broadly accessible, it can act as global public good by laying the foundation for further innovation (20). For example, global positioning system technology was developed for defense applications but has opened up other applications, including improved approaches for targeting disaster relief. The socially optimal level of investment in technological innovation requires consideration of positive and negative externalities that can have ripple effects and create spillovers across multiple stages, sectors and levels.

1.2. Innovation is Non-Linear

Innovation does not happen linearly nor is it a random process. Rather, activities in different innovation stages can occur in various chronological sequences throughout a technology's lifecycle. A well-functioning innovation system has deep connections between and a degree of co-dependence among innovation stages, making the innovation system non-linear (21). Technological change nearly always involves various feedback loops across the stages of innovation, unfolding in a chronological order that rarely traces out a linear development pathway.

The existence of feedback loops connecting activities in different innovation stages implies that overcoming barriers (or "blocking mechanisms" (22)) to innovation in any one stage often requires looking beyond that particular stage. For example, ceramic pot filters (CPFs) offer a means for users to treat available water sources in their homes and reduce the incidence of water-borne diseases. CPFs have apparent benefits, as they can be manufactured with local materials and labor. However, CPFs often lack rigorous quality control during the production process and many areas where CPFs may be deployed do not have access to an adequate supply chain for replacement parts (Table 1). Interventions to increase CPF adoption without addressing issues in the production stages are likely to deliver limited benefits.

Actors that fail to recognize the importance of feedback loops often select and promote unsuitable technologies for adoption. This problem is more prevalent when outside actors are insufficiently familiar with local settings and are passionate about specific technologies (23). Where decision-making over technology selection is split among actors, a so-called "principal-agent problem" can arise. For example, if non-governmental organizations (NGOs) and aid agencies do not adequately engage local communities, they may select inappropriate water treatment technologies on behalf of the intended users, hindering adoption.

Development of technologies in protected "niche spaces" can allow for important experimentation and early-stage user interaction to build in necessary feedback (24, 25). For example, engaging users when designing clean biomass cookstoves for Darfur has resulted in fourteen iterations of the stove, leading to more suitable designs for local cooking practices (26). To design interventions in innovation systems that build in feedback, actors must process large amounts of information concerning technologies that can address particular needs, possible policy interventions, types of financing arrangements, and input from local users.

1.3. Innovation Systems have Tipping Points

Like other complex adaptive systems, innovation systems can demonstrate punctuated equilibria whereby thresholds create irregular bursts of explosive technological change[*]. These "tipping points" in innovation systems are exemplified by past inventions, such as the steam engine, high-yield staple crops, antibiotics, the printing press, and the internet. Each example featured rapid utilization of a new invention, rich follow-on innovation, and broad societal change. Tipping points create dynamics in

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[*] Mass species extinctions, the possibility of rapid sea level rise after a certain level of climate warming, sudden outbreaks of infectious disease, and rapid economic collapse of the global financial system are examples of observed and predicted tipping points of complex adaptive systems (27).

innovation systems that are characterized by "thresholds" that create time lags and other forms of irregular technological evolution.

In some cases, innovation systems can become path-dependent or "locked-in," whereby relatively small differences in prior stages of innovation lead to large and persistent differences in which technologies achieve widespread use. Lock-in occurs through reciprocal feedback loops, such as increasing returns to an initially adopted technology through continuous adaptation and refinement (28). Lock-in can also occur when powerful actors, who may have the most to lose from changes to the status quo, bias the institutions governing innovation systems to meet their preferences and reinforce their positions of power. Lock-in poses a challenge often faced by new technologies in capital-intensive and infrastructure-dependent sectors. One example is the challenge of replacing fossil fuels with renewable energy, in which economies of scale, powerful incumbent firms, a long history of incremental process technology improvement, and the long life of physical and institutional supporting infrastructure give economic and political advantages to incumbent technologies (29). The possibility of lock-in suggests that innovation systems may reach temporarily stable equilibria of relatively static "technological regimes" (30). Lock-in builds longer time lags into the innovation system, resisting change until tipping points reorient the system and technological regimes change (30).

Meeting this challenge includes designing interventions that intentionally cross some technological tipping points (e.g. escaping from "poverty traps"), managing tipping points that have already "tipped" (e.g. increasing access to the technological outcomes of the Green Revolution), and raising barriers to avoid other tipping points altogether (e.g. catastrophic climate change).

2. Understanding the Socio-Technical Nature of Innovation Systems

Understanding innovation systems requires the integration of social and technical considerations. In innovation systems, society and technology are inextricably linked–actors shaped by institutions in society produce knowledge just as knowledge modifies and legitimizes the institutions of society. This reciprocal process is referred to as "co-production." (31–33). Co-production sheds light on the ways that technologies and innovation systems reflect broader social, political, and moral commitments of the societies in which they are embedded. Co-production also helps explain why diverse societies privilege different outcomes or forms of scientific evidence relating to technological risks and benefits over others. For example, South Korea and the United States have taken profoundly approaches to the regulation and use of nuclear energy. In the US, the perceived risk of catastrophic damage from a potential meltdown and the challenges of long-term waste disposal proved to be insurmountable challenges to the proponents of nuclear energy. In contrast, South Korean decision makers saw nuclear energy as a potential solution to what was viewed as an even bigger risk, namely failing to catch up with the living standards of the developed world. While decision makers in both countries believed that nuclear energy, in principle, could meet common goals related to energy security and economic development, the distinct socio-technical systems led to different long-term innovation pathways (33, 34).

To understand the full range of factors influencing technological change, actors intervening in innovation systems must grapple with the inextricable linkage of technology and society. As illustrated in the literature on socio-technical systems (9, 17, 30, 33), technological systems can be understood in terms of their "socio-technical characteristics" (STCs), which serve as an analytic tool to structure comparisons across the many dimensions of innovation systems. Innovation systems can be viewed through the lens of STCs to help diagnose barriers to innovation, increase the likelihood of the ex-ante identification of problems, and support learning from previous experiences.

2.1. Socio-technical Characteristics Diagnose Barriers to Innovation

STCs are a useful analytical tool for understanding and diagnosing possible barriers to innovation that may emerge when attempting to advance sustainable development in particular innovation systems. A focus on developing insights inductively through cases spanning multiple sectors with common STCs, rather than drawing strictly from one sector, location, or for certain actor groups, has great potential for developing useful generalizations.

The STC perspective can be used analytically to develop hypotheses about general conditions under which innovation systems are likely to work rather than result in barriers. The usefulness of STCs emerges from the ability of scholars and practitioners to incorporate new observations from a variety of different contexts into their knowledge base and leverage those insights to make thoughtful comparisons about potential pathways or barriers for other technologies with similar STCs.

We illustrate the STC perspective with three STCs and their associations with specific barriers to innovation that emerge from a broad range of literatures and cases: the presence of positive network externalities, perceptions of mundaneness, and modularity. These three STCs exemplify a broad range of potentially useful diagnostic STCs and are thoroughly supported by evidence in the literature. Because STCs are a guiding concept for inductive investigation, no comprehensive list of relevant STCs exists[†]. These three demonstrative STCs are certainly not the only ones that have analytic value or even the most important ones; rather, they highlight the utility of an STC-focused approach to diagnosing barriers to innovation.

2.1.1.STC: Presence of Positive Network Externalities

"The presence of positive network externalities" is an STC that describes the degree to which the adoption of a particular technology by some increases the benefits from using the technology for others (36). Users of technologies with network externalities benefit more from their use of the technology as the total number of users increases. This is exemplified by the case of industrial symbiosis, a practice to configure industrial technologies in a manner that reduces the overall impact of manufacturing by linking wastes and byproducts in one process to the input needs of another (37). The EcoTEDA industrial symbiosis program in Tianjin, China is a model where increasing the number of users has greatly expanded the value of the network by enlarging the number and robustness of possible resource exchanges between participating firms (Table 1). The role of network externalities in accelerating technology adoption suggests the importance of strategic information transmission and marketing to complement peer-to-peer information sharing.

Network externalities also suggest that technologies may be locked-in when network effects are strong and social learning is an important factor in adoption and effective utilization (28). However, developing self-sustaining networks of peers that reinforce social learning *de novo* is difficult. This dynamic is a major challenge for EcoTEDA, which has struggled to retain enough users to keep their industrial symbiosis program viable. Barriers to adoption arise unless powerful actors are able to spur the formation of self-sustaining networks. The presence of network externalities also suggests that barriers to the timely retirement of technologies are high, as users find switching to other technologies without established networks less attractive.

[†] A more extensive list of STCs is proposed in Anadon, et al., 2014 (35).

2.1.2. STC: Perceptions of Mundaneness

"Perceptions of the mundaneness of a technology" is an STC that describes the degree to which a technology fails to hold the attention of key actors in an innovation system, especially actors who play important roles in technology invention and selection. Perceptions of mundaneness tend to shift the mobilization of resources away from these options, guiding priorities towards other less appropriate or effective options (38). Technologies that draw on simpler scientific principles or approaches tend to be perceived as mundane. However, mundaneness is fundamentally determined by social perceptions, including whether a technology is considered novel or fits into pre-existing conceptions of a valuable technology.

The role of mundaneness is exemplified by the development of the system of rice intensification (SRI) in Madagascar. In the case of SRI, established research centers working on high-yield drought-tolerant seed varieties were initially skeptical of the benefits of the SRI technology, which they perceived to be a mundane, practice-based approach for improving rice yields. Instead, they preferred modern laboratory techniques for developing new hybrid and genetically-modified crops. This bias against mundane technologies led the established research community to ignore a potentially useful technology for helping small farmers (Table 1). The mundaneness STC cautions practitioners to be self-aware of institutional influences and social expectations that create perceptions unduly restricting the solution set of technologies they consider.

2.1.3.STC: Level of Modularity

"The level of modularity" is an STC that describes the degree to which a technology is comprised of design elements that are easily disaggregated and organized according to a formal architecture or plan (39). Modularity may be a direct consequence of technological design, but it may also be more directly socially constructed (e.g. in modular software design). A modular technology can therefore change via innovation in a subset of its components that are later reintegrated into the whole without complete redesign of the technology's architecture. More modular technologies have lower barriers to adaptation because the separability of components allows actors to improve one component without the architectural knowledge of the entire technology (40). This expands the range of actors who can engage in adapting a technology. Because adaptation costs are lower with increasing modularity, skilled entrepreneurial actors may be able to expand the settings in which a modular technology is suitable, thus serving a wider array of human needs.

The relationship between modularity and the expansion of suitable contexts for a technology through adaption is exemplified by the case of cookstoves (Table 1). After some success in supporting the adoption of the Berkeley Darfur Cookstove (BDS) in Darfur, Sudan, the Berkeley cookstove team sought to expand deployment of cookstoves to Ethiopia. The adaptation to accommodate different cooking practices was facilitated by the modularity of the technology: while a common shell was mass produced in India, the bulk of local adaptation was possible through the use of different pot supports.

2.2. Socio-Technical Characteristics Facilitate Learning across Innovation Systems

Practitioners with a stake in advancing sustainable development usually have direct access to only a limited set of experiences from which to develop evidence-based policy and action strategies. Too often, practitioners struggle to make innovation work for a particular need because they fail to benefit from the experience of others. This failure stems from a lack of interactions with actors working in other fields and settings, together with siloes of narrowed expertise (41). This is a lost opportunity that the identification of STCs can help address.

STCs can serve to identify barriers to innovation ex-ante and to facilitate learning. For example, the mundaneness STC can explain the degree of attention paid by actors to a technology in several of the cases in Table 1. In contrast to the case of SRI discussed above, in the case of ceramic filters, funders sometimes promoted the CPF technology because they were attracted by the idea of having local potters build low-cost water filters with local materials; in other words, the technology was not perceived as mundane because it was connected to an appealing story. However, this attention to ceramic filters at times caused other water treatment technologies to be overlooked, such as those that were already sold in the market and known by local actors.

An example of potential learning across sectors from an STC perspective is the experience from efforts to make the price of artemisinin-based combination therapy (ACT) for malaria treatment affordable for rural populations in sub-Saharan Africa and Southeast Asia. A group of global health funding organizations created a global subsidy called the Affordable Medicines Facility-malaria (AFMm) which reduced the price of ACTs to end-users. Manufacturers received the global subsidy directly and then shipped reduced-price drugs to countries. They were then supplied into informal village-level supply chains at a cost competitive with less desirable treatment options (Table 1). Here we highlight a different set of STCs that are important in this case: end-users who have limited financing and information, high prices of the technology relative to inferior alternatives, and lengthy transnational supply chains between manufacturers and end-users. The case of ACT shares similar STCs to efforts to make drought-tolerant seed varieties. Both ACT and drought-tolerant seeds are meant to be used by small-scale end-users, have high relative prices, and involve lengthy transnational supply chains. These shared STCs suggest that a similar intervention to provide a global subsidy could be considered to address the need for more affordable drought-tolerant seed varieties for farmers in developing countries.

We conclude that the community of scholars and practitioners seeking to make innovation work for sustainable development would be well served by an effort to build up a larger set of STCs along with insights derived from their application.

3. Understanding Institutional Change in Innovation Systems

Institutions shape the functioning of innovation systems by guiding and constraining the activities of actors at multiple levels, ranging from customs that extend no further than a particular village, to regional or national laws, to codified norms in international treaties (11). These institutions are often not aligned to meet sustainable development goals. Fortunately, institutions can be changed by actors who thus have the ability to reorient innovation systems towards sustainable development.

3.1. Institutions are Not Necessarily Aligned towards Sustainable Development

The complex web of existing institutions governing innovation systems reflects existing power structures. Often, such institutions are not aligned with sustainable development due primarily to three factors. First, existing institutions tend to drive innovative activity toward the areas of greatest financial prospect, not the greatest human needs. Economic incentives propel much innovation to meet the needs of those who can exert “market” or “demand pull” (42), but not those with few financial resources. The problems of neglected diseases and neglected crops, for which few new technologies have been developed, exemplify such gaps.

Second, existing institutions do not adequately govern activities producing negative externalities mediated over environmental systems or over long time-horizons. For example, private actors can often degrade the ecosystems on which human wellbeing depends without consequence. In the case of industrial symbiosis, private incentives were insufficient to drive firms to participate in an industrial symbiosis network that would have lowered overall environmental impacts in Tianjin in the short term; additional financial and regulatory incentives to reduce waste and emissions were required (Table 1).

Third, the public-good nature of knowledge, in general and of technology in particular (see Section 1.1), raises questions about the possibility for institutions to restrict the dissemination of knowledge or otherwise affect technological innovation for sustainable development. The intellectual property (IP) regime is an institution that aims to incentivize innovation by allowing inventors to exclude others from using patented technology for a fixed period of time, during which they can charge monopoly prices for patented products or earn revenues from licensing. While the IP regime strengthens incentives to invest resources in invention, it also restricts the use of new knowledge by raising prices or blocking follow-on innovation (43, 44). It has been argued that the increasingly globalized IP regime will diminish prospects for technology transfer and competition in developing countries, particularly for several important technology areas related to meeting sustainable development needs (45).

These three shortcomings of innovation systems highlight the need for institutional reform. At a national level, policy makers regularly reshape institutions to meet national interests, such as increasing domestic economic growth, improving national security, or enhancing their citizens' wellbeing. National actors may develop public policies to promote innovation to advance these interests, such as subsidizing R&D or creating publicly-funded research labs. However, many sustainable development challenges and their potential solutions have important transnational dimensions. The control of carbon emissions, the spread of infectious diseases, and the depletion of shared water resources are examples in which both problems and solutions involve multiple nation-states. Yet, transnational institutions to drive technological innovation to address these problems remain relatively weak or absent altogether, and national policies offer only patchwork solutions. To meet key sustainable development challenges, greater alignment of institutions with sustainable development goals is needed at all decision making levels.

3.2. Innovation Systems Involve Many Actors Operating at Different Stages and Levels

Reforming institutions to better align innovation systems with sustainable development requires mobilizing collective action across a complex and large set of actors, who work at many levels and who engage in activities that overlap and sometimes conflict (46, 47). As highlighted in Section 1, innovation system complexity arises because actors in the innovation system operate across different innovation stages and decision-making levels through interconnected activities. The interdependencies of actors may be explicit, such as through technology commercialization licensing agreements that involve a formal contract transferring intellectual property (48). Alternatively, linkages connecting actors may be implicit, such as the underemphasized dependence of new product development by many computer hardware and pharmaceutical firms on prior government-funded R&D (49, 50). Collective action problems arise because actors operating across different stages and decision-making levels vary in their interests and incentives, which are not necessarily driven by the goal of sustainable development. In some cases, actors are strongly driven by market forces. In other cases, a centralized authority, such as a single state or private firm, creates rules that govern the behavior of actors across all (or many) stages and decision-making levels of the innovation system.

For example, a national government usually has little motivation to take into account the needs of citizens beyond its borders, a profit-maximizing firm has insufficient incentive to invent technologies for people who cannot afford its products, and consumers lack the impetus to consider how their decisions impact other communities distant in time or space.

Aligning actors working at different decision-making levels of the innovation system is challenging. The problem is particularly relevant when needs that vary at the local level are not fully incorporated into decision-making elsewhere. In efforts over the past few decades to promote the development and adoption of cleaner and more efficient cookstoves, inventors and selectors of technologies were often not fully engaged in local contexts and lacked an adequate understanding of the needs of end-users. Many stove designs promoted by transnational actors proved unsuitable for the preparation of local dishes, which led to significant barriers in achieving widespread adoption and achieving impact (Table 1) (51).

3.3. Actors Can Change Institutions to Re-orient Innovation Systems towards Sustainable Development

The cases discussed throughout this paper illustrate how the preexisting rules and norms that shape innovation systems are not necessarily aligned towards sustainable development. However, while institutions constrain actor behavior in the short term, institutions are not immutable. The incentives, capabilities, and needs of actors that comprise innovation systems co-evolve with governing institutions (4, 52, 53). So although the capacity and power of actors depend on institutions, institutions themselves are shaped by actors and can change in both incremental and radical ways (13). For example, in the early 2000s, efforts to expand access to treatment for HIV/AIDS were hindered by stringent international IP rules that blocked developing countries from using lower-cost generic versions of HIV drugs. A global network of civil society, developing country governments, and health experts challenged the moral acceptability of these IP rules and succeeded in changing norms to allow for much greater flexibility in how patents on medicines were managed in resource-poor settings (54).

Institutions are inherently “sticky.” Changing innovation systems is a daunting task that requires leveraging multiple types of power, such as normative power to challenge the ethical acceptability of existing institutions; convening power to bring actors together to establish new goals, priorities, and agendas; legal power to negotiate and revise norms, binding rules, and standards; informational power to identify alternatives and to assess their feasibility; and financial power to create incentives, implement costly new policies, and reduce the risk or cost of doing so (35).

Here, we provide three additional examples drawn from Table 1, of how actors have induced institutional change to promote sustainable development. In the case of drip irrigation, government officials in Andhra Pradesh (AP), India designed a subsidy that reduced costs and incentivized private companies to market and disseminate knowledge of drip irrigation, a technology that could improve yields but was too expensive for most farmers in AP. Utilizing its legal power to change the rules shaping the behavior of private firms and its financial power via a subsidy to implement the new rules, the government reshaped institutions to spur widespread use of drip irrigation. In contrast, in the case of SRI, a loose network of activists, lacking both legal and financial power, relied upon informational and convening power to build a coalition of support for SRI. Finally, in the case of ACT, NGOs and academics exercised normative power through a public advocacy campaign to challenge the then-prevailing norm that donors should not subsidize relatively expensive medicines for lower-income populations.

In sum, sustainable development is not yet a strong enough organizing principle to align actor behavior in most innovation systems to systematically take into account the interests of low-income populations and future generations. Realigning innovation systems towards sustainable development requires changing institutions at all stages of the innovation process, from invention through widespread use and retirement, and at multiple decision-making levels, from local to global. While such changes may be difficult, committed actors who strategically mobilize the multiple types of power available to them have achieved significant reforms.

4. Conclusion

Technological innovation has played a central role in achieving important societal objectives, such as economic growth and improved human well-being. But innovation systems, driven primarily by markets and the most highly-resourced states, are characterized by pervasive power imbalances. As a result, the needs of marginalized populations and future generations are not met as well as they could be. Re-orienting innovation systems towards sustainable development will require addressing power imbalances and transforming many of the deeply embedded institutions that limit innovation systems from delivering on their potential. We offer three recommendations for action derived from the insights on innovation presented here, deepening and extending recommendations regarding knowledge systems more generally (55).

First, measures are needed to *regularize learning across spheres of practice* to improve understanding of how to re-orient innovation systems towards sustainable development. Understanding innovation systems and their socio-technical nature is a necessary precondition for the development of carefully targeted interventions that realize the full potential of innovation for sustainable development. Many potential lessons are available (41), but drawing appropriate conclusions requires analytical rigor, which can be facilitated by the use of STCs. Actors with convening power should facilitate learning across disparate communities of practice, for example, by organizing conferences that purposefully bring together practitioners, policymakers, and scholars working in more than one sector. Research funders should support comparative analyses that draw from the experience of more than one sector or location. Universities should teach students across disciplines to think broadly about technological innovation, and not only innovation in a single sector, region, or technology area. More broadly, actors can use STCs as heuristics to identify possible barriers to innovation that could emerge when selecting particular technologies or interventions.

Second, power disparities can be mitigated by identifying ways to s*ystematically take into account the interests of underserved populations* throughout the innovation process. Since impoverished and future populations often lack the power needed to influence innovation systems, problems arise such as when third parties select technologies poorly suited for end-users. There is also untapped potential for end-users to adapt technologies for use in new settings (25). Building in channels of communication between underserved populations and powerful actors would help alleviate power disparities and strengthen the feedback loops that characterize well-functioning innovation systems. We propose that actors with convening power and normative authority identify ways to more meaningfully engage marginalized populations in innovation systems (56). For example, international NGOs and United Nations agencies can directly engage marginalized populations when negotiating norms and establishing priorities, rather than speaking on behalf of directly-affected populations. We also argue for capacity-building among less-powerful populations to represent their interests in global forums. The gradual shift in the multilateral climate regime to policies that more deeply engage developing country governments and firms in how to innovative for climate change demonstrates that such change is possible. Previously, international organizations primarily focused on technology transfer, often through financing arrangements to export technology from more advanced countries to developing countries. However, newer forms of cooperation seek to more deeply engage developing country actors in the process of technology invention and selection by reducing information asymmetries, decreasing social distance between actors with expertise and skills, and fostering new collaborative R&D arrangements (57).

Finally, we argue that actors should *reform institutions to re-orient innovation systems towards sustainable development*, leveraging various forms of power to do so. Due to the complex-adaptive nature of innovation systems, such reforms will be more effective if all stages of innovation and all relevant decision-making levels are considered at the outset. To illustrate: reform efforts in the biomedical innovation system previously focused on just one stage, such as driving invention for neglected diseases, adapting vaccines to be heat-stable, or decreasing the price of HIV/AIDS medicines. More recently, institutional reforms under consideration involve using publicly-financed "push" and "pull" incentives that simultaneously steer invention towards socially negotiated goals and facilitate widespread adoption by building affordability measures into R&D processes from their inception. Governments of both industrialized and developing countries are being asked to contribute to a global biomedical R&D fund for this purpose (58), an illustration of reforming institutions simultaneously at both national and global levels.

In the context of climate change mitigation, institutional reform to create a carbon price through regional, national, and sub-national carbon markets has shifted the incentives facing consumers and producers towards low-carbon forms of energy at all stages of innovation. For example, carbon pricing increases the profitability of private action to invest in renewable energy invention, select more energy-efficient appliances, and hasten the retirement of greenhouse gas-intensive power plants. Yet carbon pricing alone may be inadequate for addressing climate change in a cost-effective manner. Doing so also requires further strengthening incentives for private energy R&D and concerted public R&D investment (59).

Many types of interventions are needed to realign innovation systems for sustainable development, requiring actors to leverage the types of power available to them. Altering the institutions governing innovation systems may appear politically or practically impossible in the short-run. Yet without institutional change, certain populations will remain excluded from the benefits of innovation, and the interests of present generations will continue to unfairly outweigh those of the future. Making technological innovation work for sustainable development requires making fundamental changes to the rules of the game.

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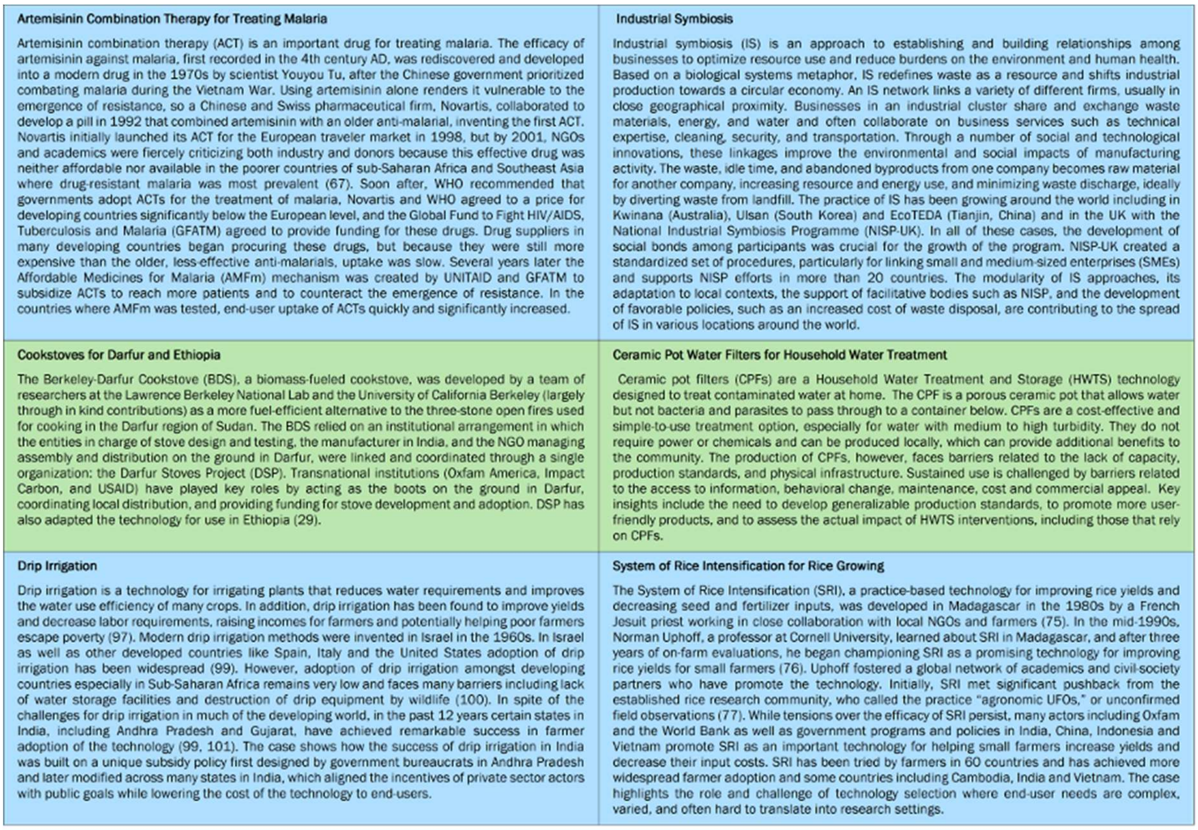
Figure Legends

Figure 1. Summaries of six case studies of technologies and innovation systems to promote sustainable development. The cases are detailed further in the Supporting Information.



Artemisinin Combination Therapy for Treating Malaria

Artemisinin combination therapy (ACT) is an important drug for treating malaria. The efficacy of artemisinin against malaria, first recorded in the 4th century AD, was rediscovered and developed into a modern drug in the 1970s by scientist Youyou Tu, after the Chinese government prioritized combating malaria during the Vietnam War. Using artemisinin alone renders it vulnerable to the emergence of resistance, so a Chinese and Swiss pharmaceutical firm, Novartis, collaborated to develop a pill in 1992 that combined artemisinin with an older anti-malarial, inventing the first ACT. Novartis initially launched its ACT for the European traveler market in 1998, but by 2001, NGOs and academics were fiercely criticizing both industry and donors because this effective drug was neither affordable nor available in the poorer countries of sub-Saharan Africa and Southeast Asia where drug-resistant malaria was most prevalent (67). Soon after, WHO recommended that governments adopt ACTs for the treatment of malaria, Novartis and WHO agreed to a price for developing countries significantly below the European level, and the Global Fund to Fight HIV/AIDS, Tuberculosis and Malaria (GFATM) agreed to provide funding for these drugs. Drug suppliers in many developing countries began procuring these drugs, but because they were still more expensive than the older, less-effective anti-malarials, uptake was slow. Several years later the Affordable Medicines for Malaria (AMFm) mechanism was created by UNITAID and GFATM to subsidize ACTs to reach more patients and to counteract the emergence of resistance. In the countries where AMFm was tested, end-user uptake of ACTs quickly and significantly increased.

Industrial Symbiosis

Industrial symbiosis (IS) is an approach to establishing and building relationships among businesses to optimize resource use and reduce burdens on the environment and human health. Based on a biological systems metaphor, IS redefines waste as a resource and shifts industrial production towards a circular economy. An IS network links a variety of different firms, usually in close geographical proximity. Businesses in an industrial cluster share and exchange waste materials, energy, and water and often collaborate on business services such as technical expertise, cleaning, security, and transportation. Through a number of social and technological innovations, these linkages improve the environmental and social impacts of manufacturing activity. The waste, idle time, and abandoned byproducts from one company becomes raw material for another company, increasing resource and energy use, and minimizing waste discharge, ideally by diverting waste from landfill. The practice of IS has been growing around the world including in Kwinana (Australia), Ulsan (South Korea) and EcoTEDA (Tianjin, China) and in the UK with the National Industrial Symbiosis Programme (NISP-UK). In all of these cases, the development of social bonds among participants was crucial for the growth of the program. NISP-UK created a standardized set of procedures, particularly for linking small and medium-sized enterprises (SMEs) and supports NISP efforts in more than 20 countries. The modularity of IS approaches, its adaptation to local contexts, the support of facilitative bodies such as NISP, and the development of favorable policies, such as an increased cost of waste disposal, are contributing to the spread of IS in various locations around the world.

Cookstoves for Darfur and Ethiopia

The Berkeley-Darfur Cookstove (BDS), a biomass-fueled cookstove, was developed by a team of researchers at the Lawrence Berkeley National Lab and the University of California Berkeley (largely through in kind contributions) as a more fuel-efficient alternative to the three-stone open fires used for cooking in the Darfur region of Sudan. The BDS relied on an institutional arrangement in which the entities in charge of stove design and testing, the manufacturer in India, and the NGO managing assembly and distribution on the ground in Darfur, were linked and coordinated through a single organization: the Darfur Stoves Project (DSP). Transnational institutions (Oxfam America, Impact Carbon, and USAID) have played key roles by acting as the boots on the ground in Darfur, coordinating local distribution, and providing funding for stove development and adoption. DSP has also adapted the technology for use in Ethiopia (29).

Ceramic Pot Water Filters for Household Water Treatment

Ceramic pot filters (CPFs) are a Household Water Treatment and Storage (HWTS) technology designed to treat contaminated water at home. The CPF is a porous ceramic pot that allows water but not bacteria and parasites to pass through to a container below. CPFs are a cost-effective and simple-to-use treatment option, especially for water with medium to high turbidity. They do not require power or chemicals and can be produced locally, which can provide additional benefits to the community. The production of CPFs, however, faces barriers related to the lack of capacity, production standards, and physical infrastructure. Sustained use is challenged by barriers related to the access to information, behavioral change, maintenance, cost and commercial appeal. Key insights include the need to develop generalizable production standards, to promote more user-friendly products, and to assess the actual impact of HWTS interventions, including those that rely on CPFs.

Drip Irrigation

Drip irrigation is a technology for irrigating plants that reduces water requirements and improves the water use efficiency of many crops. In addition, drip irrigation has been found to improve yields and decrease labor requirements, raising incomes for farmers and potentially helping poor farmers escape poverty (97). Modern drip irrigation methods were invented in Israel in the 1960s. In Israel as well as other developed countries like Spain, Italy and the United States adoption of drip irrigation has been widespread (99). However, adoption of drip irrigation amongst developing countries especially in Sub-Saharan Africa remains very low and faces many barriers including lack of water storage facilities and destruction of drip equipment by wildlife (100). In spite of the challenges for drip irrigation in much of the developing world, in the past 12 years certain states in India, including Andhra Pradesh and Gujarat, have achieved remarkable success in farmer adoption of the technology (99, 101). The case shows how the success of drip irrigation in India was built on a unique subsidy policy first designed by government bureaucrats in Andhra Pradesh and later modified across many states in India, which aligned the incentives of private sector actors with public goals while lowering the cost of the technology to end-users.

System of Rice Intensification for Rice Growing

The System of Rice Intensification (SRI), a practice-based technology for improving rice yields and decreasing seed and fertilizer inputs, was developed in Madagascar in the 1980s by a French Jesuit priest working in close collaboration with local NGOs and farmers (75). In the mid-1990s, Norman Uphoff, a professor at Cornell University, learned about SRI in Madagascar, and after three years of on-farm evaluations, he began championing SRI as a promising technology for improving rice yields for small farmers (76). Uphoff fostered a global network of academics and civil-society partners who have promote the technology. Initially, SRI met significant pushback from the established rice research community, who called the practice "agronomic UFOs," or unconfirmed field observations (77). While tensions over the efficacy of SRI persist, many actors including Oxfam and the World Bank as well as government programs and policies in India, China, Indonesia and Vietnam promote SRI as an important technology for helping small farmers increase yields and decrease their input costs. SRI has been tried by farmers in 60 countries and has achieved more widespread farmer adoption and some countries including Cambodia, India and Vietnam. The case highlights the role and challenge of technology selection where end-user needs are complex, varied, and often hard to translate into research settings.