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Innovation and Access to Technologies for Sustainable Development: Diagnosing Weaknesses and Identifying Interventions in the Transnational Arena

Laura Diaz Anadon *(Harvard Kennedy School),* Kira Matus *(London School of Economics),* Suerie Moon *(Harvard School of Public Health),* Gabriel Chan *(Harvard Kennedy School),* Alicia Harley *(Harvard Kennedy School),* Sharmila Murthy *(Suffolk University Law School),* Vanessa Timmer *(One Earth),* Ahmed Abdel Latif *(International Centre for Trade and Sustainable Development),* Kathleen Araujo *(Harvard Kennedy School),* Kayje Booker *(Forward Montana),* Hyundo Choi *(Chosun University),* Kristian Dubrawski *(McKinsey),* Lonia Friedlander *(Stony Brook University),* Christina Ingersoll *(MIT Sloan),* Erin Kempster *(Massachusetts Department of Public Utilities),* Laura Pereira *(University of Cape Town),* Jennie Stephens *(Clark University),* Lee Vinsel *(Stephens Institute of Technology) and* William C. Clark *(Harvard Kennedy School)*

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Abstract

Sustainable development – improving human well-being across present generations without compromising the ability of future generations to meet their own needs – is a central challenge for the 21st century. Technological innovation can play an important role in moving society toward sustainable development. However, poor, marginalized, and future populations often do not fully benefit from innovation due to their lack of market or political power to influence innovation processes. As a result, current innovation systems fail to contribute as much as they might to meeting sustainable development goals. This paper focuses on how actors and institutions operating in the transnational arena can mitigate such shortfalls.

To identify the most important transnational functions required to meet sustainable development needs our analysis undertook three main steps. First, we developed a framework to diagnose blockages in the global innovation system for particular technologies. This framework was built on existing theory and new empirical analysis. On the theory side, we drew from the literatures of systems dynamics; technology and sectoral innovation systems, science and technology studies, the economics of innovation, and global governance. On the empirical front, we conducted eighteen detailed case studies of technology innovation in multiple sectors relevant to sustainable development: water, energy, health, food, and manufactured goods. We use the framework to analyze our case studies in the common language of (1) technology stocks, (2) non-linear flows between stocks substantiated by specific mechanisms, and (3) characteristics of actors and socio-technical conditions (STCs) which mediate the flows between stocks . We identify blockages in the innovation system for each of the cases, diagnosing where in the innovation system flows were hindered and which specific sets of STCs and actor characteristics were associated with these blockages. Figure E.1 displays the components of our framework and how they relate.

Keywords: innovation system, technology, sustainable development, energy, health, agriculture, water, manufacturing

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It is available at http://www.hks.harvard.edu/centers/mrcbg/programs/sustsci/documents/papers/2014-01. Professor Bill Clark has approved this paper for inclusion in the working paper series. Comments are welcome and may be directed to the author, Laura_Diaz_Anadon@hks.harvard.edu.

Author Biographies:

Laura Diaz Anadon is assistant professor of Public Policy at the Harvard Kennedy School (HKS), and associate director of the Science, Technology, and Public Policy program and co-faculty chair of the Energy Technology Innovation Policy research group, both at the Belfer Center for Science and International Affairs at HKS. Her research focuses on energy- and environment-oriented technological progress and seeks to: identify and quantify the diverse benefits that derive from it; map the complex factors (including institutions) that contribute to it; and create tools for policymakers to manage the systemic uncertainties that accompany it. She also studies the coupling between water, energy and food systems and its policy implications. Laura has worked on policy projects for various organizations (e.g., Climate Strategies on a World Bank project and the International Energy Agency). Her work has been published in journals including *Environmental Science & Technology*, *Energy Policy*, *Issues in Science & Technology*, *and Energy Economics*, and she is working on finalizing Cambridge University Press book on “Transforming U.S. Energy Innovation”. In addition to her work on energy innovation, systems analysis, and the water-energy-food nexus, Laura has published in chemical engineering and nuclear magnetic resonance journals, carried out process engineering research projects at DuPont and Bayer Pharmaceuticals and Johnson Matthey Catalysts, and worked as a financial consultant for banks on credit risk models for financing technology projects. Laura holds a Ph.D. in Chemical Engineering from the Magnetic Resonance and Catalysis Group at the University of Cambridge (UK), a Master in Public Policy from the Harvard Kennedy School, and a Master in Chemical Engineering from the University of Manchester (UK). She has also studied and worked on research at the University of Stuttgart (Germany).

Kira Matus is an Assistant Professor in Public Policy and Management in the Department of Government of the London School of Economics. She is the Project Co-Director of the “Innovation and Access to Technologies for Sustainable Development” project in the Sustainability Science Program (SSP), and a SSP Visiting Fellow from 2012-present. Prior to joining the LSE in 2010, Dr. Matus was a Senior Policy Analyst at the Yale Center for Green Chemistry and Green Engineering. Dr. Matus received her PhD in Public Policy from Harvard University in 2009, where she was a doctoral fellow in sustainability science in the Sustainability Science Program from 2007 to 2009. From 2007-2009, she was a recipient the U.S. Environmental Protection Agency's (EPA) Science to Achieve Results (STAR) Graduate Fellowship. Dr. Matus also has an SM in Technology and Policy from MIT, and an ScB in Chemistry from Brown University.

Suerie Moon, MPA, PhD is Research Director and Co-Chair of the Forum on Global Governance for Health at the Harvard Global Health Institute. She is also a Lecturer in the Department of Global Health and Population at the Harvard School of Public Health, where she teaches a course on global governance and health. She also co-directs the Project on Innovation and Access to Technologies for Sustainable Development, Sustainability Science Program, at the Harvard Kennedy School of Government. Her work focuses on global governance, the political economy of global health (with a focus on innovation, access to medicines, intellectual property and equity), the evolution of international regimes, and innovative policies for addressing global problems. Prior to coming to Harvard, she worked for the Médecins Sans Frontières/Doctors Without Borders (MSF) international Campaign for Access to Essential Medicines, where she focused on intellectual property policies, ensuring equitable pricing of medicines, and research and development into neglected diseases. She has also consulted for a number of international non-governmental organizations, think tanks, and intergovernmental organizations. Dr. Moon is a member of the editorial board of PLoS Medicine, Board of Directors of MSF-USA, the Drugs for Neglected Diseases Initiative-North America, the expert Proposal Review Committee of UNITAID, the Global Advisory Committee of the WHO project on local production for access to medical products, and the Chatham House Global Health Working Group on Financing. Her work has appeared in the New England Journal of Medicine, PLoS Medicine, Health and Human Rights, Globalization and Health, Global Health Governance, The Scientist, and other publications. She is the author (with Wolfgang Hein) most recently of the book: Informal Norms in Global Governance: Human Rights, Intellectual Property and Access to Medicines (Ashgate 2013). She received a BA in History from Yale University, an MPA from the Woodrow Wilson School of Public and International Affairs at Princeton University, and a PhD in Public Policy from the Harvard Kennedy School of Government.

Gabe Chan is a Public Policy Ph.D. student and a Doctoral Research Fellow in the the Energy Technology Innovation Policy group, the Harvard Environmental Economics Program, and a former fellow of the Sustainability Science Program, at the Harvard Kennedy School of Government. His research focuses on innovation economics and policy in the energy sector using quantitative social science methodology. His interests lie in the interaction of government policy with radical technical change as well as in developing and applying cutting-edge statistical methodology to empirical questions in innovation economics, such as the estimation of technological spillovers from public R&D. Gabe is a recipient of the Belfer Center Science, Technology, and Public Policy Fellowship (2012-2014), the Giorgio Ruffolo Sustainability Science Fellowship (2011-2012), the Vicki Norberg Bohm Fellowship (2010), and a graduate of the Harvard Graduate Consortium on Energy and the Environment (2012). Prior to coming to Harvard, Gabe graduated from the Massachusetts Institute of Technology in 2009 where he received Bachelor of Science degrees in Earth, Atmospheric, and Planetary Science, and Political Science. In 2007 and 2009, Gabe worked at the U.S. Department of Energy where he worked in the Climate Change Technology Program (CCTP), an interagency group tasked with prioritizing the federal government's investments and policies for mitigating climate change through accelerated technology innovation and deployment.

Alicia Harley is a doctoral candidate in Public Policy and a Giorgio Ruffolo Doctoral Research Fellow in the Sustainability Science Program at Harvard's Kennedy School of Government. She is interested innovation in agriculture systems and specifically how to govern innovation to improve the well-being of the most vulnerable farmers. She uses a mix of qualitative and quantitative methods, relying heavily on organizational behavior and institutional approaches in political science. Her dissertation investigates the agriculture innovation system in India. Her two main projects investigate the agriculture innovation system first comparatively across several States in India focusing specifically on drip irrigation, and second within a single State (Bihar) where she works within a single village to understand the adoption dynamics and multiple State and Federal Policies in place to support agriculture development. Using a structural systems model of the innovation system, she aims to expand the literature in innovation studies to include a greater focus on innovation in the context of power asymmetries and inequality. Alicia leads the food and agriculture systems working group as part of a collaborative project with the Initiative on Innovation and Access to Technologies for Sustainable Development led by Professor William Clark. She received her BA, magna cum laude, in Environmental Science and Public Policy and a citation in Arabic from Harvard College in 2008 and subsequently worked as a greenhouse gas reduction program coordinator for Harvard's Office for Sustainability. Following that, she spent a year in Cairo as a Fulbright Scholar researching the political economy of agriculture and food security in Egypt before returning to graduate school to begin her PhD.

Sharmila L. Murthy is an Assistant Professor at Suffolk University Law School. She is also a Visiting Scholar with the Sustainability Science Program, Mossavar-Rahmani Center for Business and Government, and an Associate Fellow of the Human Rights to Water and Sanitation Program, Carr Center for Human Rights Policy, both at the Harvard Kennedy School of Government.

Vanessa Timmer is co-founder and Director of the One Earth Initiative. From 2006-2008, Vanessa was Project Manager (External Relations) at Metro Vancouver (formerly Greater Vancouver Regional District – GVRD) as part of the Sustainable Region Initiative which brings together private sector, municipal governments, civil society and other partners to stimulate ideas and action around sustainability. Vanessa holds a Ph.D. in Resource Management and Environmental Studies from the University of British Columbia. Her dissertation focused on organizational structure and strategy of Friends of the Earth International and Greenpeace, and on their ability to adapt to change. From 2002 until 2003, Vanessa was a Fulbright Research Fellow at the Kennedy School of Government at Harvard University as part of the Initiative on Science and Technology for Sustainability. She holds a Bachelor of Arts (Honours) in Sociology from Queen's University and a M.Sc. in Environmental Change and Management from the University of Oxford.

Ahmed Abdel Latif is Senior Programme Manager for Innovation, Technology and Intellectual Property at the Geneva based International Centre for Trade and Sustainable Development (ICTSD), since November 2007. Previous to date, he was with the Permanent Mission of Egypt to the United Nations and the World Trade Organization (WTO) in Geneva (2000-2004) where he was a delegate to the TRIPS Council and to the World Intellectual Property Organization (WIPO). More recently, he was Giorgio Ruffolo Research Fellow in the Sustainability Science Program at the Kennedy School of Government, Harvard University (fall term, 2012). He holds an LL.M in Public International Law (London School of Economics and Political Science), a BA in Political Science (American University in Cairo) and the Diplôme of the Institut d'Etudes Politiques de Paris (Sciences Po Paris).

Kathleen Araújo is a Research Fellow in the Science, Technology and Public Policy program at the Belfer Center for Science and International Affairs at Harvard University's Kennedy School of Government. She works on issues relating to the management of national energy-environmental systems; science and technology; as well as institutional aspects of industrial oversight. Her recent research includes a comparative analysis of national transitions to nuclear, geothermal, wind, and biofuels technologies; as well as changes in the R&D/intellectual property activity of the international chemical industry. She has consulted for inter-governmental organizations and partnered on initiatives with the Massachusetts Institute of Technology Energy Education Task Force and American Academy of Arts and Sciences. Araújo completed her Ph.D. at MIT.

Kayje Booker received her PhD in Environmental Science, Policy, and Management from UC Berkeley in 2011. Her graduate work focused on the sociocultural aspects of technologies designed for the global poor, particularly improved biomass cookstoves, and of policy instruments, such as carbon markets, designed to incentivize innovation in these technologies. Kayje also received a MS in Range Management from Berkeley and has explored the possible effects of various carbon policies for management of rangelands in the United States. Now living in Missoula, Montana, Kayje is the CEO of a

non-profit, Forward Montana, that seeks to train, mobilize, and elect the next generation of leaders in Montana.
Hyundo Choi is an Assistant Professor at Chosun University. After earning his doctoral degree from Seoul National University, he worked as a postdoctoral fellow in the Energy Technology Innovation Policy research group at the Belfer Center in Harvard Kennedy School. His research is concerned with economics of technological innovation, focusing on the industry evolution and social networks. He also has a strong interest in technological transition process for sustainability.

Kristian Dubrawski is a sustainability and environmental engineering researcher and consultant. He is currently a post-doctoral fellow at the University of British Columbia, where his research investigates water science, technology, and policy for rural Canada. Previously, he was a consultant at McKinsey & Company, where he worked predominantly with the Sustainability and Resource Productivity and Public Sector Practice on clean energy and water technology development and policy. Kristian holds a Ph.D. in Chemical and Biological Engineering from the University of British Columbia. He has also worked on research at Lawrence Berkeley National Laboratory (with A. Gadgil and Arsenic-free Bangladesh), and Harvard Kennedy School (with L. Diaz Anadon in Sustainability Science) on the role of energy innovation in meeting global sustainable development goals.

Lonia Friedlander is currently completing a doctoral degree in geochemistry at Stony Brook University and anticipates graduating in December of 2014. She also holds a Master of Science degree in Water Management from Ben Gurion University of the Negev in Sde Boqer, Israel, which she completed in 2010. She received her Bachelor of Arts degree from Washington University in St. Louis in 2008, double majoring in Chemistry and Earth and Planetary Science. While working toward her masters degree, she studied the use of drip irrigation technology by smallholder farmers in sub-Saharan Africa. This experience sparked her ongoing interest in technology transfer for global sustainability. Lonia has received numerous awards for her academic work, including the Astronaut Foundation Scholarship and the Courtney Werner Memorial Prize in Earth and Planetary Sciences. She was also a finalist for the Hertz Foundation Fellowship and recently spent a year of her doctoral studies at the University of Poitiers in Poitiers, France on a Chateaubriand Fellowship. She also received the 2011 Excellence in Teaching Award for her work as a TA in the Geosciences Department at Stony Brook University.
Lonia has presented her work at numerous academic conferences. Her most recent oral presentation, at the 51st Annual Meeting of the Clay Mineral Society, was awarded 3rd Place in the Graduate Student Oral Presentation competition. Her work has been published in several international journals, including *Agricultural Systems, Agricultural Water Management,* and *Journal of Water and Health,* a publication of the International Water Association. She has also contributed to the proceedings of several conferences, including *ICARUS II: Cool Heads for a Hot World* and *The Lunar and Planetary Sciences Conference*. Lonia's primary research interest is combining results from the hard sciences with understanding from the social sciences to provide innovations that can positively impact and increase global sustainability.

Christina Ingersoll is the manager of Strategy and Systems Integration for the Committee on Sustainability Assessment (COSA), and special projects coordinator for the Sustainability Initiative at MIT Sloan. An environmental scientist, Christina has been working on issues related to sustainable agriculture since 1998. She worked for the Agricultural Sustainability Institute University of California (Davis) on the Sustainable Sourcing Project and was a Teaching Fellow and Research Fellow with the Sustainability Science Program at the Harvard Kennedy School from 2010-2013, as well as a contributor to the Project on Innovation and Access to Technologies for Sustainable Development. She worked at the International Food Policy Research Institute as a co-author on the publication Food security, farming, and climate change to 2050: Scenarios, results, policy options. She also worked with the Sustainable Food Lab as a quantitative specialist and co-developer of a tool for assessing the climate change impacts of agricultural practices. Ms. Ingersoll received a MBA and Certificate in Sustainability from the MIT Sloan

School of Management, and a degree in Biology and Environmental Science with honors from Carleton College.
Erin Kempster joined the Energy group of the Project on Innovation and Access to Technologies for Sustainable Development as a research assistant for the summer of 2012, after earning her Master of Arts in Law and Diplomacy from The Fletcher School of Law and Diplomacy at Tufts University. During her graduate studies, Erin assisted with research through The Fletcher School's Center for International Environment and Resource Policy and was named a 2011-2012 graduate fellow with the Tufts Institute of the Environment. Prior to study at The Fletcher School, Erin graduated from Williams College with a Bachelor of Arts in English.

Laura Pereira is currently a post-doctoral research fellow at the University of Cape Town where she is working on a project looking at orphan crop innovation. The work that she conducted for this case study was undertaken while she was a Giorgio Ruffolo post-doctoral fellow and Gundle Public Service fellow in the Sustainability Science Program at the Harvard Kennedy School of Government. Laura Pereira completed her DPhil at the University of Oxford in 2012 where she looked at adaptive capacity of the private sector to climate change impacts in the food system. An ecologist by training, she now focuses on bridging the natural and social sciences through research that has taken her to South Africa, Brazil, Colombia, Mozambique and Nigeria.

Jennie C. Stephens is an associate professor of Environmental Science and Policy at Clark University in Worcester Massachusetts, USA, and she is an associate of the Energy Technology Innovation Policy Group at Harvard's Kennedy School. Stephens' teaching, research, and community engagement focuses on socio-political aspects of energy technology innovation, renewable energy, and climate change education/awareness. She has contributed to understanding the social dynamics of innovation of wind power, carbon capture and storage, and smart grid technology. Her work also explores stakeholder engagement in sustainable innovation, the role of universities in sustainable transitions, and communication among different actors including "experts" and the public. Stephens received her Ph.D. (2002) and M.S. (1998) at the California Institute of Technology in Environmental Science and Engineering and her B.A. (1997) from Harvard in Environmental Science and Public Policy. Before joining the faculty of Clark University, she did post-doctoral research at Harvard's Kennedy School and she taught courses at Tufts, Boston University, and MIT. Stephens' research has been published in multiple journals including Energy Policy, Environmental Science and Technology, Climatic Change, Global Environmental Change, Environmental Communication and Technological Forecasting and Social Change. She is currently working on a book to be published by Cambridge University Press on "The Promise of Smart Grid: Competing Perspectives and Visions".

Lee Vinsel is an assistant professor of Science and Technology Studies at Stevens Institute of Technology. He received a PhD in History and Policy at Carnegie Mellon University before completing a joint postdoctoral fellowship with Harvard University's Kennedy School of Government and School of Engineering and Applied Sciences. His work focuses on the relationship between governance and technological change. He is particularly interested in the effects that different policy and regulatory mechanisms have on innovation as well as in policy mechanisms that aim to shape user behavior rather than technological artifacts. His book manuscript examines the history of automotive regulation in the United States from 1893 to the present. It uses untapped archival collections to study how insurance executives, psychologists, engineers, lawyers, medical doctors, and many other kinds of actors shaped cars and drivers in an attempt to decrease risks.

William Clark is the Harvey Brooks Professor of International Science, Public Policy and Human Development at Harvard University's John F. Kennedy School of Government. His research focuses on sustainability science: understanding the interactions of human and environmental systems with a view toward advancing the goals of sustainable development. He is particularly interested in how institutional arrangements affect the linkage between knowledge and action in the sustainability arena. At Harvard, he currently co-directs the Sustainability Science Program. He is co-author of *Adaptive environmental assessment and management* (Wiley, 1978), *Redesigning rural development* (Hopkins, 1982), and *The global health system: Institutions in a time of transition* (Harvard, 2010); editor of the *Carbon dioxide review* (Oxford, 1982); coeditor of *Sustainable development of the biosphere* (Cambridge, 1986), *The earth transformed by human action* (Cambridge, 1990), *Learning to manage global environmental risks* (MIT, 2001), and *Global Environmental Assessments* (MIT, 2006); and co-chaired the US National Research Council's study *Our Common Journey: A Transition Toward Sustainability* (NAP, 1999). He serves on the editorial board of the *Proceedings of the National Academy of Science*. Clark is a member of the National Academy of Sciences and a Fellow of the American Association for the Advancement of Science. He is a recipient of the MacArthur Prize, the Humboldt Prize, the Kennedy School's Carballo Award for excellence in teaching, and the Harvard College Phi Beta Kappa Prize for Excellence in Teaching.

Sustainability Science Program

The Sustainability Science Program at Harvard University harnesses the University's strengths to promote the design of institutions, policies, and practices that support sustainable development. The Program addresses the challenge of sustainable development by:

- advancing scientific understanding of human-environment systems;
- improving linkages between research and policy communities; and
- building capacity for linking knowledge with action to promote sustainability.

The Program supports major initiatives in policy-relevant research, faculty research, training of students and fellows, teaching, and outreach. See http://www.hks.harvard.edu/centers/mrcbg/programs/sustsci.

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Executive Summary

Sustainable development – improving human well-being across present generations without compromising the ability of future generations to meet their own needs – is a central challenge for the 21st century. Technological innovation can play an important role in moving society toward sustainable development. However, poor, marginalized, and future populations often do not fully benefit from innovation due to their lack of market or political power to influence innovation processes. As a result, current innovation systems fail to contribute as much as they might to meeting sustainable development goals. This paper focuses on how actors and institutions operating in the transnational arena can mitigate such shortfalls.

To identify the most important transnational functions required to meet sustainable development needs our analysis undertook three main steps. First, we developed a framework to diagnose blockages in the global innovation system for particular technologies. This framework was built on existing theory and new empirical analysis. On the theory side, we drew from the literatures of systems dynamics; technology and sectoral innovation systems, science and technology studies, the economics of innovation, and global governance. On the empirical front, we conducted eighteen detailed case studies of technology innovation in multiple sectors relevant to sustainable development: water, energy, health, food, and manufactured goods. We use the framework to analyze our case studies in the common language of (1) technology stocks, (2) non-linear flows between stocks substantiated by specific mechanisms, and (3) characteristics of actors and socio-technical conditions (STCs) which mediate the flows between stocks. We identify blockages in the innovation system for each of the cases, diagnosing where in the innovation system flows were hindered and which specific sets of STCs and actor characteristics were associated with these blockages. Figure E.1 displays the components of our framework and how they relate.

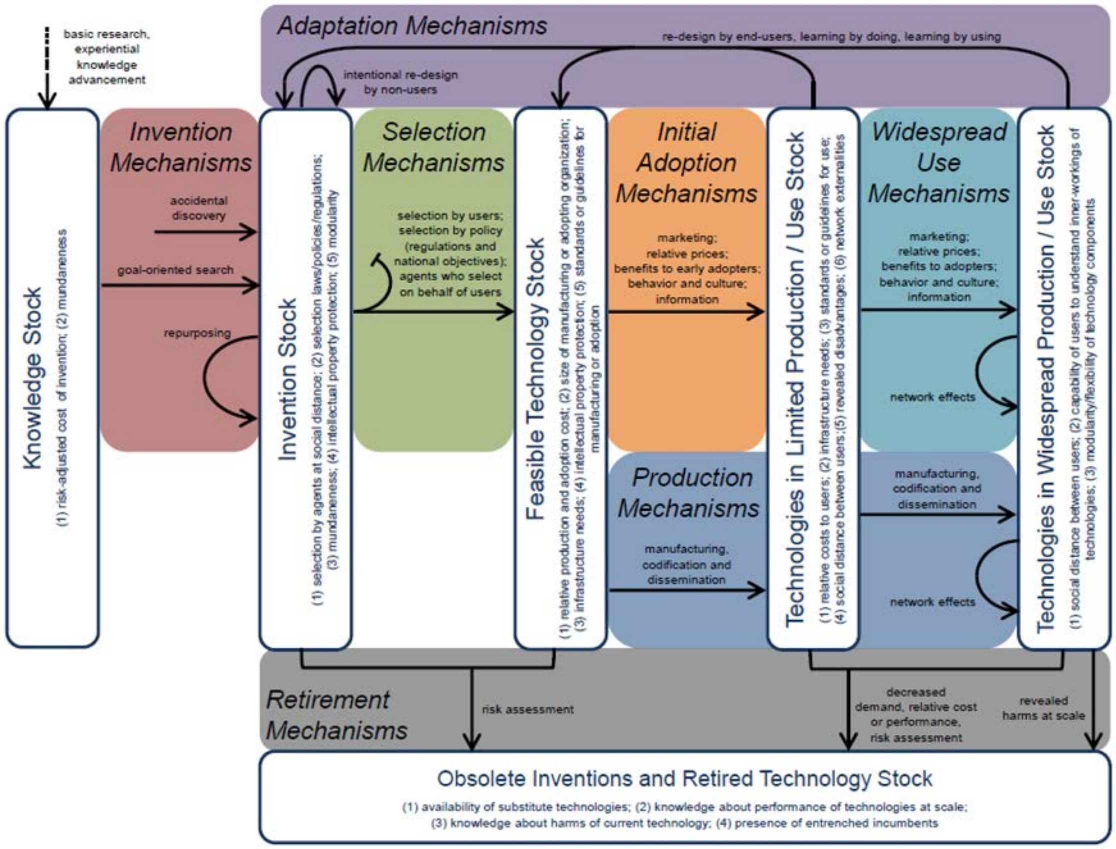

Figure E.1. Schematic of a framework to model an innovation system

Second, after identifying the blockages in each case study, we compared the cases and extracted the set of STCs that were correlated with blockages of specific flows in multiple case studies. Figure E.2 lists the six flows out of the different stocks and the relevant STCs that affected the ease of flow.

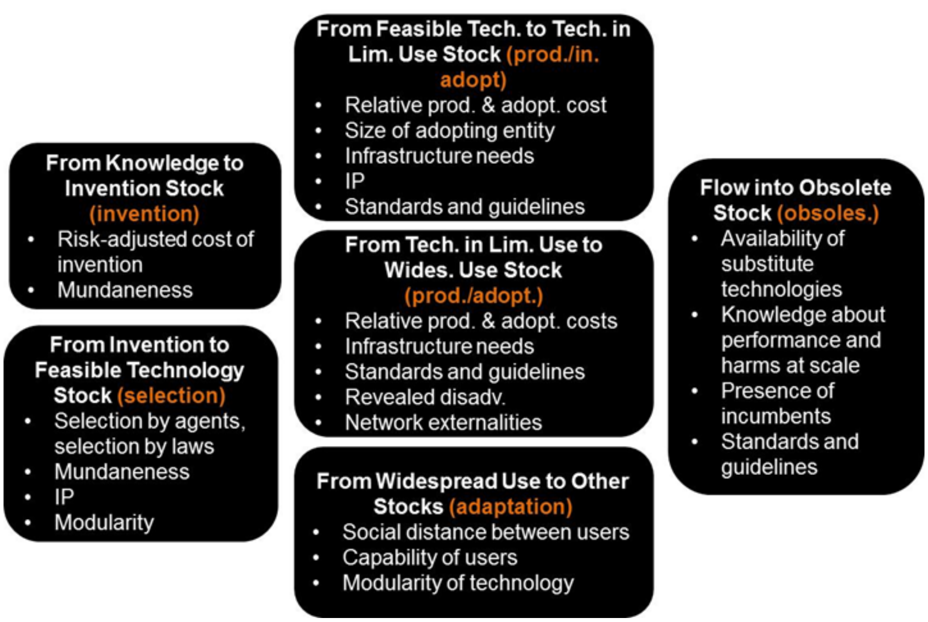

Figure E.2. **Socio-technical characteristics grouped by the stocks for which they affect flow rates**

In the third and final step, we used the STCs to develop a classification of eight types of functions that can be implemented in the transnational arena to address these systematic blockages: First, "core" functions are those that must be performed at the transnational level because they cannot be performed adequately by any one nation-state: (1) negotiating transnational/global norms, rules and standards and (2) managing transnational externalities. Second are "facilitating" functions that can make the global innovation system work more efficiently: (3) setting transnational/global goals, priorities and agendas and (4) providing strategic information to reduce information asymmetries. Finally "supportive" functions are those needed for countries with a shortage of necessary resources: (5) reducing social distance between local populations and transnational actors; (6) building capacity; (7) reducing (financial) costs, and (8) reducing risk. Finally, we note that different resources are required to perform these functions. For example, some actors may have convening authority to help set global goals, priorities and agendas, whereas others may have financial resources. A central objective is to understand which actors or institutions may be well-suited to perform specific functions in specific cases, for which we rely on the STC analysis.

Combining the STC-based analysis with transnational functions allowed us to formulate more general hypotheses that we believe are likely to hold across sectors and technologies. For example, we hypothesize that:

- Technologies that are characterized by very high risk-adjusted invention costs (e.g., heat-stable vaccines, cancer drugs and carbon capture and storage) are unlikely to be invented without either large markets or large public investments. In these cases, internationally pooled funds could reduce costs and risks.
- Technologies that are mundane and have a high social distance between inventors and users (e.g., cookstoves and ceramic water filters) are unlikely to receive systematic and concerted efforts for invention. Targeted R&D funding, transnational convening, and information gathering would enable a more directed and connected invention process to meet end-user needs.
- When users are individuals or small organizations with limited capabilities (e.g., drip irrigation), and the technology requires significant levels of local adaptation, widespread use is not likely without a champion and a process for enabling replication. Transnational actors and institutions could build capacity through training and information provision.
- Technologies that require complementary infrastructure and support services (e.g., mobile applications for sanitation and solar panels in microgrids) will not be widely adopted in the absence of investments in such infrastructure.

In light of our analysis covering a wide range of cases across different areas of need, we conclude that there are several types of interventions that would benefit from the involvement of transnational actors or institutions, for example:

1. Financial underwriting to support invention of technologies with high risk adjusted cost of invention,
2. Providing information and expertise through extension-like services where the capability of adopters is low and/or infrastructure needs are high, and
3. Using convening power to strengthen networks between those who invent, select, adapt and use technologies in cases where there is a high social distance between these groups.

The most appropriate actors or institutions to perform these functions will depend on the technological and social contexts of any case- in other words, on the STCs, as well as on the characteristics of the transnational actors or institutions themselves.

Part 1. Introduction: Technological innovation, globalization & sustainable development

Sustainable development – improving human well-being across present generations without compromising the ability of future generations to meet their own needs – is a central challenge for the 21st century.[1] The development of new technologies has played a major role in improving the lives of billions of people. Yet technology has also been the source of major harm to the environment, to the health and well-being of individuals, and to societies at large. That being said, technological innovation[2] in a range of sectors, such as agriculture, water, energy, health, and manufacturing,[3] can play a central role in achieving sustainable development. Examples of

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1 UN. (1987). Our Common Future: Report of the World Commission on Environment and Development. Report of the World Commission on Environment and Development A/42/427. [And:] Annan, Kofi. (2000). We, the Peoples: The Role of the United Nations in the 21st Century. New York: United Nations.

2 We adopt Harvey Brooks' definition of technology as "knowledge of how to fulfill certain human purposes in a specifiable and reproducible way," and his definition of innovation as "the process by which technology is conceived, developed, codified, and deployed," underscoring that innovations must be widely deployed or adopted to have impact. [Brooks, H. (1980). Technology, Evolution, and Purpose. Daedalus 109(1): 65–81.] This definition allows us to consider technology as a broader concept than merely a physical artifact. Following Brian Arthur's work, we include devices and methods or processes, as well as "assemblages of practices and components" and the "collection of devices and engineering practices available to a culture." [Arthur, W.B. (2009). The Nature of Technology: What It Is and How It Evolves. New York: Free Press.]

3 *For energy*: Schock, R.N., Fulkerson, W., Brown, M.L., San Martin, R.L., Green, D.K. and Edmonds, J. (1999). How much is energy research and development worth as insurance? Annu. Rev. Energy Environ. 24: 487–512. [And:] Davis, S.J., Cao, L., Caldeira, K., and Hoffert, M.I. (2013). Rethinking wedges. Environmental Research Letters v.8, doi:10.1088/1748-9326/8/1/011001. *For health*: WHO Consultative Expert Working Group on Research and Development (CEWG): Financing and Coordination. (2012). Research and Development to Meet Health Needs in Developing Countries: Strengthening Global Financing and Coordination. Geneva: World Health Organization. (Report of the Consultative Expert Working Group on Research and Development: Financing and Coordination). [And:] WHO Ad Hoc Committee on Health Research Relating to Future Intervention Options. (1996). Investing in Health Research & Development: Report of the Ad Hoc Committee on Health Research Relating to Future Intervention Options. TDR/Gen/96.1. Geneva: World Health Organization. *For manufacturing:* National Research Council (U.S.). Committee on Grand Challenges for Sustainability in the Chemical Industry. (2006). Sustainability in the Chemical Industry Grand Challenges and Research Needs. Washington, D.C.: National Academies Press. http://www.nap.edu/catalog.php?record_id=11437. [And:] Evans, Steve. (2009).Towards a Sustainable Industrial System: With Recommendations for Education, Research, Industry and Policy. Cambridge, U.K.: University of Cambridge. *For water:* UN Water. (2008). Status report on Integrated Water Resources Management and Water Efficiency Plans: Preparedness for the 16th session of the Commission on Sustainable Development - May 2008. Retrieved from http://www.unwater.org/downloads/UNW_Status_Report_IWRM.pdf. [And:] UN ESCWA. (2001). The Role of Desalinated Water in Augmentation of the Water Supply in Selected ESCWA Member Countries (United Nations Economic and Social Commission for Western Asia). [And:] Kundzewicz, Z.W., Mata, L.J., Arnell, N.W., Döll, P., Kabat, P., Jiménez, B., Miller, K.A., Oki, T., Sen, Z., and Shiklomanov, I.A. (2007). Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. [And:] Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., and Hanson, C.E. (Eds). Cambridge, U.K.: Cambridge University Press, 173–210. [And:] Grey, D., and Sadoff, C.W. (2007). Sink or Swim? Water security for growth and development. Water Policy 9(6): 545. doi:10.2166/wp.2007.021. [And:] Davis, S. and Skinner, D. (2012). The role of science and values in setting sustainable diversion limits (Committee for Economic Development of Australia). Retrieved from http://www.ceda.com.au/media/271676/waterprojectdavisskinnerfinal.pdf. [And:] 2030 Water Resource Group. (2009). Charting our Water Future: Economic Frameworks to Inform Decision-Making. Retrieved from http://www.mckinsey.com/App_Media/Reports/Water/Charting_Our_Water_Future_Exec%20Summary_001.pdf. [And:] Rygaard, M., Binning, P.J., and Albrechtsen, H.-J. (2011). Increasing urban water self-sufficiency: New era, new challenges. Journal of Environmental Management 92(1): 185–194. doi:10.1016/j.jenvman.2010.09.009. [And:] Zhou, Y.

potentially useful technologies include: farming practices that reduce the need for water or pesticides while improving farmer incomes, household water purification devices, wastewater reuse techniques, low-carbon energy generating technologies, cookstoves that generate less indoor air pollution, health products (e.g., vaccines, drugs, diagnostics, other medical devices), and less hazardous manufacturing processes for consumer goods. Calls for enhancing innovation to support sustainable development have been featured in every major review of sustainability science.[4] Furthermore, ongoing debates over the post-2015 Development Agenda raise the possibility of global agreement on an ambitious set of Sustainable Development Goals in the areas of energy, food, health, water and a clean environment, among others. Although we are inching closer to what these goals are, there has been far less attention to how we can achieve them. In other words, who should do what, when and at what level, and which norms and rules are required to promote the production and use of the knowledge needed to achieve broadly-shared sustainable development objectives? Of particular concern to this project is how to ensure that innovation meets the needs of the world's poorest, most marginalized or vulnerable, who often do not reap the benefits of technological change.

The literature on innovation systems largely focuses on national and sub-national systems[5] or on specific sectors.[6] However, the intensified cross-border movement of knowledge and ideas,[7] capital, goods,[8] services, and people[9] that characterizes globalization makes the concept of "national innovation systems" less empirically accurate and conceptually useful than it once was on its own. In

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and Tol, R.S.J. (2005). Evaluating the costs of desalination and water transport. Water Resources Research 41(3). doi:10.1029/2004WR003749. [And:] World Bank. (May 2010). Water Hackathon: Lessons Learned. Water Papers. Available at: http://www.un.org/waterforlifedecade/pdf/2012_world_bank_water_hackathon_lessons.pdf. *For agriculture*: Klerkx, L., Hall, A. and Leeuwis, C. (2009). Strengthening Agricultural Innovation Capacity: Are Innovation Brokers the Answer? International Journal of Agricultural Resources, Governance and Ecology 8(5-6): 409–438. [And:] Ruttan, V.W. (2001). Technology Growth and Development: An Induced Innovation Perspective. New York: Oxford University Press. [And:] Pardey, G. and Beddow M. (2013). Agricultural Innovation: The United States in a Changing Global Reality. The Chicago Council on Global Affairs.

4 Conway, G., and Waage, J. (2010). Science and Innovation for Development. London: UK Collaborative on Development Sciences (UKCDS).

5 Freeman, C. (1987). Technology Policy and Economic Performance: Lessons from Japan. London: Frances Pinter. [And:] Freeman, C., and Lundvall, B.-A. (Eds). (1988). Small Countries Facing the Technological Revolution. New York: Pinter Publishers. [And:] Lundvall, B.-A. (1992). National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning. London: Frances Pinter. [And:] Nelson, R.R. (Ed). (1993). National Innovation Systems – A Comparative Analysis. Oxford, U.K.: Oxford University Press. [And:] Cooke, P., Uranga, M.G. et al. (1997). Regional Innovation Systems: Institutional and Organisational Dimensions. Research Policy 26: 475–491. [And:] Amsden, A.H. (2003). Beyond Late Development: Taiwan's Upgrading Policies. Cambridge, MA: MIT Press. [And:] Amsden, A.H. (2001). The Rise of "the Rest" : Challenges to the West from Late-Industrializing Economies. New York: Oxford University Press. [And:] Nelson, R. (2005).Technology, Institutions, and Economic Growth. Cambridge, MA: Harvard University Press.

6 While the former focuses on political/geographic units of analysis, the latter focuses on a set of products for specific uses across borders (Malerba, 2002). Pavitt, K. (1984). Patterns of Technical Change: Towards a Taxonomy and a Theory. Research Policy 13: 343–74. [And:] Malerba, F. (2002). Sectoral systems of innovation and production. Research Policy 31(2): 247–264.

7 Ruttan, V.W. (2001). Technology, Growth, and Development : An Induced Innovation Perspective. New York: Oxford University Press.

8 Eaton, J., and Kortum, S. (2004).Technology, Geography, and Trade. Econometrica 70(5):1741–1779.

9 Abella, M. (2006). Global competition of skilled workers and consequences. In: Kuptsch, C., and Fong, P.E. (Eds). Competing for Global Talent. International Institute for Labour Studies.

other words, the innovation process has become increasingly transnational in nature,[10] as is recognized by the work on sectoral innovation systems. Transnational actors, such as intergovernmental organizations, private multinational firms, or international NGOs, are already playing crucial roles in innovation for sustainable development,[11]and should be taken more explicitly into account in any analysis of the system.[12] Examples of transnational actors active today include the World Bank's Clean Development Mechanism, the Montreal Protocol's Multilateral Fund, the International Finance Corporation, Consultative Group on International Agriculture Research, and numerous not-for-profit public-private partnerships working to develop drugs for neglected diseases. Furthermore, transnational or global institutions play an increasingly important role in shaping the innovation process. Examples of such institutions include global norms regarding the right to food, water, energy, health and a clean environment; voluntary regulatory systems; and the World Trade Organization (WTO) Agreement on Trade Related Aspects of Intellectual Property Rights (TRIPS). Improving the impact of innovation on human well-being requires a better understanding of this emergent global innovation system, both to diagnose its weaknesses and identify ways to strengthen it. We argue for greater attention to an emerging global innovation system, which we define as the **actors and institutions whose interactions shape the innovation process beyond national borders** in different technology areas. We also argue for the need for a framework for analyzing the innovation process at different scales in a way that is informed by experiences in (and applicable to) a wide range of technologies and sectors.

All innovation systems are faced with the well-known challenges of overcoming market failures linked to the positive externalities of knowledge creation (e.g., spillovers),[13] scientific limitations (e.g., knowledge may be insufficient to generate a desirable invention), and risks inherent in developing

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10 Ernst, D. (January 2002). Global Production Networks and the Changing Geography of Innovation Systems. Implications for Developing Countries. Economics of Innovation and New Technology 11(6): 497–523. [And:] Pietrobelli, C., and Rabellotti, R. (July 2011). Global Value Chains Meet Innovation Systems: Are There Learning Opportunities for Developing Countries? World Development 39(7): 1261–1269. doi:10.1016/j.worlddev.2010.05.013.
11 UN. (2012). Launch of United Nations Sustainable Development Solutions Network. New York City, September 24. Retrieved from http://unsdsn.org/2012/09/24/launch-of-united-nations-sustainable-development-solutions-network/. [And:] Koehn, P.H. (2004). Sustainable development frontiers and divides: Transnational actors and US/China greenhouse gas emissions. International Journal of Sustainable Development & World Ecology 11(4): 380–396. Retrieved from http://www.tandfonline.com/doi/pdf/10.1080/13504500409469841.
12 Steering Committee of the State-of-Knowledge of Standards and Certification. (2012). Towards Sustainability: The Roles and Limitations of Certification. Washington, D.C.: RESOLVE, Inc. Retrieved from http://www.resolv.org/site-assessment/towardsustainability/.
13 Griliches, Z. (1992). The Search for R&D Spillovers. Scandinavian Journal of Economics 94: S29-S47. The policy problem posed by goods with large positive or negative externalities has long been a concern to scholars and practitioners. One class of such goods are public goods (those that are non-excludable and non-rival), and within these are a particular sub-group known as global public goods (public goods that are non-excludable and non-rival on a global scale). Information and knowledge are classic examples of global public goods. The information component of technologies may fall anywhere along the spectrum from pure public goods to club goods to private goods; notably, institutions may, in some cases, be able to effectively move a good from one category to another (e.g., by making it more or less excludable). Because of the central role of knowledge in technology, the extent to which SD-relevant knowledge is available as a global public good and the effectiveness of existing institutions to generate sufficient levels of such knowledge can be highly problematic, given the classic problem of underprovision of public goods. See: Kaul I., Grunberg, I., and Stern, M.A. (Eds). (1999). Global Public Goods: International Cooperation in the 21st Century. Oxford, U.K.: Oxford University Press.

and utilizing new technologies (e.g., uncertainty regarding commercial value of a product, uncertainty regarding impacts on human health or the environment).[14]

Three additional challenges arise for technologies that may serve sustainable development goals:

First is intragenerational equity – ensuring that innovation meets the needs of the poorest, most marginalized or vulnerable communities *today*. For example, the needs of many of the poor attract little R&D investment, leading to a situation of "neglected diseases" for which no effective medicines exist, "neglected crops" which have not been improved by the advances of crop science, irrigation systems that do not deliver adequate water for farming, or the relatively small number of consumer products for less wealthy markets, such as cleaner indoor cookstoves. Together, these issues can broadly be understood as a problem of "neglected populations."[15]

Second is intergenerational equity – taking into account the needs of *future generations*. For example, too little is being done today to reduce the future risk of catastrophic climate change, to ensure adequate sources of water for future farmers, or to prevent manufacturing waste products from depositing persistent pollutants into the environment.

For both intra- and intergenerational equity, markets alone are unlikely to drive adequate innovative effort, since poor and future populations do not provide strong market incentives. While public policy is likely to be needed to intervene in the market, the political power of poor, marginalized populations and future generations to shape such policies is relatively weak. Increasing the contribution of technological advances to sustainable development requires measures to expand the inclusiveness of benefits within present *and* future generations, and because of the globalization of innovation systems, it is likely that at least some such measures need to be transnational in nature.

This leads us to our **third** challenge, which is building transnational institutions to address sustainable development needs in a world of sovereign (often competing) states with disparate capacities and goals within their national innovation systems. Such institutions are required to respond to transnational or global challenges involving cross-border externalities, such as climate change.[16] Examples of other such externalities include the transfer of pathogens, toxic substances, and unhealthy lifestyles across borders; the globalized nature of food commodity markets; the

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[14] Part of this argument is captured by the infant industry literature. E.g.: Mill, J.S. (1848). Principles of political economy. In: Robson, J.M. (Ed.). Collected Works of John Stuart Mill, vol. III. University of Toronto Press, pp. 918 – 919. [And:] Melitz, M.J. (2005). When and how should infant industries be protected? Journal of International Economics 66:177–196. See also: Scherer, F.M. and Harhoff, D. (2000). Technology policy for a world of skew-distributed outcomes. Research Policy 29: 559–566.

[15] Moon, S., Bermudez, J., and 't Hoen, E. (2012). Innovation and Access to Medicines for Neglected Populations: Could a Treaty Address a Broken Pharmaceutical R&D System? PLoS Med. 9(5): e1001218. Retrieved from http://www.plosmedicine.org/article/info%3Adoi%2F10.1371%2Fjournal.pmed.1001218

[16] Stern, N. (2007). Review on the Economics of Climate Change. Cambridge, U.K.: Cambridge University Press. [And:] Nordhaus, W.D. (1993). Reflections on the Economics of Climate Change. The Journal of Economic Perspectives 7(4): 11–25. Retrieved from http://www.econ.yale.edu/~nordhaus/homepage/climate_change_jpe_1993.pdf.

depletion of internationally-shared water resources; and the globally-interlinked nature of production systems.

Indeed, in our review of the literature across five sectors,[17] we found many examples in which the existing innovation system failed to deliver technologies to address the needs of present but marginalized and/or future generations.

In this paper, we seek to contribute to existing scholarship on innovation in two ways:

a) By providing a **comprehensive conceptual model** of the innovation process that is applicable **across scales** (local, national, regional, global), **sectors** (agriculture, water, energy, health and manufacturing), **types of technology** (tangible and intangible, small and large-scale, etc.), and all stages of the innovation process **from invention to retirement**. This inductively-developed framework **provides an analytic tool for evaluating innovation systems** across sectors and scales. While this model was developed through the literature and case studies of technologies that (at least at some point) were found to be particularly relevant for sustainable development, some of the project's concepts may be useful for studying technological innovation more broadly.
b) By expanding the conceptualization of innovation systems to explicitly include the **global level,** and using the above-mentioned conceptual model to analyze what actors and institutions can do at the transnational level under different conditions to better support innovation for sustainable development.[18]

Part 2 describes our methods and key definitions. Part 3 presents our general conceptual model of the innovation process. Part 4 presents the socio-technical conditions that are likely to impede flows from stock to stock. Part 5 distills the transnational functions that actors and institutions could perform to overcome these impediments, depending on the particular sociotechnical conditions. Finally, Part 6 synthesizes our conclusions on how to utilize the framework and our preliminary thoughts on how to strengthen the global innovation system to better realize the potential of technological innovation for sustainable development.

Part 2. Methods and Key Definitions

The scholarly community has not yet widely adopted a common language, conceptual framework, or set of practical guidelines for analyzing the global innovation system or the possible role that transnational actors could play. This project sought to pull together disparate strands of scholarship and practical experience through an analysis of the existing literature, alongside eighteen new case

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[17] The five sectoral background papers are now in draft and will be made available on the project website.
[18] Which has already been suggested in: Cozzens, S.E., and Catalán, P. (2008). Global Systems of Innovation: Water Supply and Sanitation in Developing Countries. Paper presented in the VI Globelics Conference, September 22–24, Mexico City. http://www.tpac.gatech.edu/sites/default/files/Cozzens%20%26%20Catalan_Global_System.pdf

studies and consultation with experts across sectors to develop such a language, conceptual framework, and guidelines. We have iteratively and inductively developed a conceptual framework that facilitates analysis across different sectors, technologies and scales. This conceptual framework is not specific to those technologies that (at least on some dimension) have been considered relevant to sustainable development, though that is the subset of particular interest to this project.

As noted above, we have defined the global innovation system as the actors and institutions whose interactions shape the innovation process beyond national borders. "Actors" are individuals and/or organizations with agency in the system, including individuals such as farmers, scientists or entrepreneurs, and organizations such as governmental bodies (e.g., US Trade Representative), intergovernmental organizations (e.g., WHO, FAO, World Bank), private firms (e.g., Syngenta, Bechtel, Merck), not-for-profit entities (e.g., Oxfam, foundations, industry associations), research entities (e.g., universities, private or public laboratories), and community-based organizations (e.g., South Africa's Treatment Action Campaign). Key actors may also include collaborative entities that link multiple organizations, such as public-private partnerships. The relevant actors may be public, private, academic, non-profit, or hybrid, and may operate from the local to the global levels.

In contrast, "institutions" refer to sets of formal and informal rules, norms, decision-making procedures, beliefs, and expectations that govern the interaction of actors.[19] Actors both shape and are shaped by institutions. Examples of formal institutions relevant for innovation include national patent laws and the TRIPS Agreement, the Convention on Biological Diversity, the dispute-settlement procedures of the WTO, human rights treaties, and sustainable development goals such as those articulated in the Rio+20 Declaration. Notably, over the past two decades, international norms regarding the rights to water, health, food, energy, and a clean environment have evolved substantially,[20] suggesting increasing global interest, willingness – and arguably even sense of responsibility – to contribute to technological innovation for sustainable development. Examples of informal institutions include norms of data-sharing within epistemic communities, information feedback loops between actors in a supply chain, the role of markets in resource allocation, and societal expectations of the behavior of transnational corporations in developing countries. We understand technologies to be inseparable from, and to co-evolve with, the social institutions that shape how they are invented and adopted. Institutions may be constructed at the local, regional, national, or global scale.

Actors and institutions that comprise the global innovation system include those that may be based in one country but exert influence across borders – they do not necessarily need to be "international" in the conventional sense but do need to have transnational reach. For example, we saw in one of the case studies that we conducted (listed in Table 1) that local farmers developing an

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[19] Krasner, S.D. (1982). Structural Causes and Regime Consequences: Regimes as Intervening Variables. International Organization 36(2).

[20] Yamamoto, A., and Moon, S. (July 2013). Evolving international norms on technologies for sustainable development: a historical review on scientific progress, food, water & sanitation, health, energy, and manufacturing. Working Paper. Paper to be available on project website.

improved system of rice cultivation in Madagascar may work locally, but if their technology has benefits in other countries or regions we would consider these farmers to be significant actors in the global innovation system. Maximizing the potential global contributions of that knowledge would be considered an important systemic objective.

Following other scholars, we take a broad definition of "technology" that goes beyond physical artifacts: "technology includes devices and methods or processes," as well as "assemblages of practices and components" and the "collection of devices and engineering practices available to a culture."[21]

For this project, we were particularly interested in diagnosing the barriers likely to inhibit the evolution of a technology from initial invention to widespread use to retirement. As noted above, poor and marginalized populations in the present generation and future generations often do not exert adequate market demand to induce market forces to provide technologies to meet their needs. In addition to the well-identified problem of insufficient market-pull, we also sought to identify and illuminate the many other types of barriers that can impede the innovation process. This required grappling with barriers relating not only to the technologies themselves, but also the social contexts within which they operate (for example, power asymmetries between those with decision making authority and the most marginalized populations).

The eighteen case studies which we used to develop and test the conceptual framework span the five sectors of interest and are listed in Table 1. Each technology we selected was presented by its advocates as intended to enhance sustainable development in some fashion, usually by being designed to bring benefits to the poor, or to future generations. We recognize that few, if any, technologies are unambiguously beneficial, that all entail trade-offs, and that the ultimate impacts may be known only many years after they are introduced. This project did not seek to evaluate the ultimate contributions (or harms) to sustainable development provided by each technology, nor to endorse any particular one. Rather, we were interested in analyzing technologies designed in part to promote benefits for those who might not normally be able to exert "demand pull" on the innovation system.

We also purposely chose cases where transnational actors or institutions have played an important role in developing a novel "system intervention." Emphasis was placed on selecting cases that were representative of different types of "system interventions" and that highlighted different elements of the global innovation system. For example, some involved intergovernmental actors, such as UNICEF, while others were the results of networks of individuals, transnational private sector entities, national governments, or the work of NGOs. The actual interventions varied from the interjection of funding, to on-the-ground application, to the use of advisors to help with adjustments of technologies to local contexts. The technologies also differed across their degree of development

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[21] Brooks, H. (1980). Technology, Evolution, and Purpose. Daedalus 109(1): 65–81. This is echoed in: Arthur, W.B. (2009). The Nature of Technology : What It Is and How It Evolves. New York: Free Press.

and penetration in potential markets. For example, some technologies were well developed and in use, while others were still in earlier phases of invention or adoption. The cases were also selected to cover technologies that were very different from each other (e.g., technologies that are mainly devices versus technologies that are mainly practices, technologies that are used by individuals versus technologies that are used by large firms, and technologies that are very capital intensive versus some that are far less so). The cases were analyzed in detail using a common template that facilitated the comparative analysis. In addition, several other cases were studied but included only as vignettes in a series of sectoral background papers used to develop an initial innovation system framework.[22] The findings generated during the case study analysis are summarized in Part 4.

Table 1. List of 18 case studies developed in this project

Case	Description
1. Energy: Carbon Capture and Storage – FutureGen, United States	This case study investigated the evolution of the FutureGen project, which for many years was the flagship effort of the US government to build the first commercial-scale facility capturing CO_2 from a coal power plant in Illinois. In its first incarnation, project costs were estimated at over $1 billion and it had participation from other national governments (which were contributing expertise and some funds to the project) to foster learning. The current version has been significantly scaled down and has no participation from other governments, (its partners are limited to federal and state government agencies and one technology provider). This case includes a comparison with the EU New Entrants Reserve program supporting CCS in various geologies in the EU and China's GreenGen project.
2. Energy: Cookstoves – Lawrence Berkeley National Laboratory, Darfur, Sudan	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 managed to reach significant and lasting technology adoption. It 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. 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 adoption. The case also includes the adaptation of the technology for its use in Ethiopia
3. Energy: Solar Photovoltaics-Grameen Shakti, Bangladesh	This case study investigated the barriers for solar household systems (SHS) in rural low-income regions for access to renewable electricity, and the interventions of Grameen Shakti (GS), a private company, in promoting SHS in Bangladesh. GS was initially funded by the Grameen Bank and the World Bank, but eventually became economically self-sufficient through two unique mechanisms: 1) financing and distribution mechanisms to establish themselves as a for-profit business with a social mission, and 2) mechanisms to establish a long-term grassroots maintenance and support network throughout rural Bangladesh. Through these two mechanisms, GS has become the largest off-grid solar distributor in the world. This case also includes a comparison of countries where these two mechanisms could be successfully employed to expand the global adoption of SHS.
4. Energy: Geothermal Energy Generation,	The case of Kenyan geothermal development serves as a reference of how barriers to technology adoption, including knowledge gaps and financial risk, can be overcome in the innovation process. In this case, decades of episodic interest and adoption are followed by a quadrupling of installed geothermal capacity since 2000. The change translates as a relative shift from negligible, geothermal

[22] Soon to be available online as Harvard Sustainability Science Program Working Papers.

Kenya	contributions in the electricity mix to what now is nearly a quarter of the power mix. The importance of institution-building and finance by transnational actors is broadly considered, as the government seeks to scale with new industry partners. Specifically, risk reduction by finance/aid organizations is explored, alongside capacity-building by the UNEP, African Rift Geothermal Development Facility, and United Nations University-Geothermal Program. Regional gains in technology learning are also covered.
5. Agriculture: Biopesticides, Kenya	This case study looks at the development of specific biopesticide products in Kenya, finding that partnership between international research organizations and private sector companies was essential for overcoming barriers in selection and initial adoption. In addition transnational résumés played an important role: European cut-flower environmental standards provided a demand-pull for the adoption of biological control agents by Kenyan flower producers and thus provided a market for private sector firms to produce and distribute biopesticdes in Kenya.
6. Agriculture: Cassava Bread. Nigeria	This case study looks at the establishment of non-traditional urban markets for cassava through the development of High Quality Cassava Flour (HQCF) being incorporated into baked goods, most notably bread. The innovative technology includes both the means of processing the cassava into HQCF as well as the method of making cassava bread.
7. Agriculture: Cocoa Genome	The case study is a historical analysis of the motivations, development, and innovation steps that the Cocoa Genome Project went through in order to map and publish the genome of a variety of Theobroma cacao (the cocoa tree) with the goal of facilitating research and development of disease and pathogen resistant, locally applicable strains of T. cacao and thereby improving the production possibilities for cocoa farmers
8. Agriculture: Drip Irrigation, India and Africa	Drip irrigation's water use efficiency shows potential for increasing agricultural intensification without exhausting freshwater resources. In addition, drip may also help poor farmers escape poverty, by improving yields and decreasing labor requirements. Yet, many barriers to its use remain, impeding the access of those most in need of drip technology. This case analyzes the development of the exceptionally successful Israeli drip irrigation technology and its use there, contrasting it with either partly successful (India) or almost wholly unsuccessful (Africa) efforts to promote the use of drip irrigation.
9. Agriculture: System of Rice Intensification, Bihar India	The System or Rice Intensification (SRI) is a methods based technology for improving yields and decreasing inputs including water and seeds in rice cultivation. The technology was developed and popularized out of Madagascar, and has since spread to over 50 countries in Asia, Africa and Latin America. This case study looks at the development of SRI and reviews the adoption of SRI on a global scale, but then zooms into Bihar to look at the challenges and opportunities of adoption of SRI by vulnerable farmers in the poorest state in India. The case finds that the invention stage of SRI represents an important example of a technology "bubbling up" from users and that selection and promotion were largely driven by a small number of key visionary "champions" at international, regional and local scales.
10. Manufacturing: Industrial symbiosis	This case analyses a variety of projects arranged around the principles of industrial ecology that exist in many countries, coordinated by facilitating and consultative organisations. Many multilateral organisations are active in studying, promoting, and facilitating industrial symbiosis. Initial funding and training have often been provided by multilateral organizations, with adaptations occurring at local levels.
11. Manufacturing: Textiles / Higg Index	This is a case of cooperative innovation between major retailers in the apparel supply chain. In this case, global adoption and implementation are key to success; it relies on global actors and global supply chains. Invention and selection are driven by large corporations largely in North America and the EU, who then work with global suppliers on adoption and adaptation.
12. Water: Wastewater reuse, Australia	This case study examines wastewater reuse in Australia and the Middle East. While this technology is often appropriate in arid environments, numerous cultural and political barriers exist to adoption. To be effective, the use of "recycled" water requires long-term political commitment and

and Middle East	appropriate infrastructure.
13. Water: Ceramic pot filters, Ghana	This case study focuses on the use of ceramic pot filters (CPFs) in Ghana and other parts of the world. CPFs have been widely promoted as a low-cost and simple-to-use option for treating water at home, especially water with medium to high turbidity. Their widespread adoption is challenged by numerous cultural and production barriers. Moreover, the zeal and enthusiasm that donors and aid agencies have traditionally shown for household water treatment and storage, like CPFs, needs to be critically examined to assess the true impact of these projects.
14. Water: Mobile apps for Water-Sanitation, India	This case study focuses on the increasing use of mobile applications to expand and improve water, sanitation and hygiene services (i.e., "mWASH"). The main barriers to adoption relate to cultural barriers and beliefs, lack of capacity, infrastructure challenges and costs. However, evidence also suggests that many of these barriers could be overcome through effective adaptation. Several key insights that may be of particular interest to transnational actors are drawn, such as an institutional culture of openness.
15. Health: Heat stable vaccines – US, global	This case examines the evolution of a student-founded company, Vaxess, which secured intellectual property rights to a technology for the heat-stabilization of vaccines first developed by academic scientists at Tufts University, and succeeded in advancing it through several stages of development. The effort relied on an ad hoc network of supporters, including early-stage financial support provided by several parties at Harvard, the non-profit product development organization PATH, the US CDC, and finally, support from a venture capitalist. This development path is unusual in the high-cost, high-risk and high-technology world of vaccine development, which is dominated by a few large firms. If successful, the technology may be picked up by multinational vaccine producers based in the US, Europe and possibly also India. The vaccines would ultimately be purchased by governments and donors such as GAVI and UNICEF, and used in many LMICs
16. Health: Ready Use Therapeutic Foods/Plumpy' nut – France, many food insecure countries	This case focuses on Ready-to-use Therapeutic Food (RUTF), a simple technology that revolutionized the treatment of severe acute malnutrition. A basic paste of nuts, oil and milk solids helps malnourished children recover quickly at home and minimizes the need for children and their caregivers to stay for long periods of time in in-patient care. It was initially developed by a French scientist partnering with the French firm Nutriset, field-tested by international NGO Doctors Without Borders and later adopted widely by the humanitarian aid community. It became controversial recently due to conflicts over patent rights on RUTF, efforts to produce it locally, and concerns that using it to address chronic malnutrition may undermine local food economies and food security.
17. Health: Affordable Medicines Facility- Malaria – sub-Saharan Africa, Southeast Asia, US, Switzerland	This case examines the evolution of a global subsidy for artemisinin-combination therapy (ACT), the current gold-standard for treating malaria. ACTs were often unavailable and too costly for those living in rural areas of sub-Saharan Africa or Southeast Asia, where resistance to older, cheaper drugs rendered them almost useless. A global subsidy on ACTs was implemented to simultaneously reduce the price of ACTs to the same level as older anti-malarials, while delaying the emergence of resistance linked to use of artemisinin monotherapy (not in combination) and improving availability in rural areas by tapping into the private sector. This case study discusses how the subsidy came about, reviews the evidence on how well it performed in achieving its intended objectives, and discusses potential applications of global subsidies to other technologies for sustainable development.
18.Health: Access to cancer treatment and care in India – India	This case examines recent debates over access to cancer drugs in India, and more broadly, access to a package of treatment and care. The incidence of cancers is growing in India, a country with a growing affluent class but also hundreds of millions of people living in abject poverty. Access to the newer generation of cancer medicines has recently become a politically high-profile topic. India is a major producer of low-cost generic pharmaceuticals for both developing and industrialized countries, and amended its patent law in 2005 to comply with WTO obligations, but preserved

	certain public health flexibilities. It has used such flexibilities, such as compulsory licenses and high patentability criteria, on drugs for kidney cancer, leukemia and HER2+ breast cancer. This case study examines the subsequent impact on price, other measures required to increase access to cancer care in India, and what functions transnational actors may play to improve the response to cancer.

Part 3. Conceptual Framework to Diagnose the Innovation Process for a Particular Technology

Drawing on the field of systems dynamics,[23] we conceptualized the innovation process as six **stocks** with technologies moving from one stock to another through seven inter-linking, interacting and non-linear **flows** enabled by different **mechanisms** and characterized by **socio-technical conditions**. The stocks represent six different states of technology: (1) knowledge, (2) invention, (3) feasible technology, (4) technology in limited production and use, (5) technology in widespread production and use; and (6) Obsolete and retired technology. The seven flows are: (a) invention, (b) selection, (c) production, (d) early adoption, (e) widespread use, (f) adaptation, and (g) retirement. Our conceptual model of the innovation system is illustrated in Figure 1.

Table 2. Summary of Elements of the Innovation Process

Stocks and Flows	**Mechanisms Enabling Flows Between Stocks**
1. **Knowledge Stock**	
a) Invention Flow →	Mechanisms for Invention i) Goal-oriented search ii) Accidental discovery iii) Repurposing
2. **Invention Stock**	
b) Selection Flow →	Mechanisms for Selection i) Selection by users ii) Selection by policy (regulations and national objectives) iii) Selection by agents who select on behalf of users
3. **Feasible Technology Stock**	
c)Production Flow →	Mechanisms for Production i) Manufacturing ii) Codification and dissemination
d) Early Adoption Flow* →	Mechanisms for Early Adoption

[23] System dynamics is a powerful methodology for framing, understanding, and discussing complex policy issues and problems. It helps untangle the complexity of *connections* by providing a *language* and set of *tools* to describe – and even model – the cause-and-effect relationships among various variables. Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., and Rickne, A. (2008). Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Research Policy 37(3): 407–429. See the following book for a seminal contribution: Forrester, J.W. (1961). Industrial Dynamics. Cambridge, MA: The MIT Press. Reprinted by Pegasus, Communications, Waltham, MA.

	i) Marketing ii) Relative prices iii) Benefits to early adopters iv) Behavior and culture v) Information
4. **Technology in Limited Production &Use Stock**	
e) Widespread Use Flow →	Mechanisms for Widespread Use i) Marketing ii) Relative prices iii) Benefits to adopters iv) Behavior and culture v) Information
f) Adaptation Flow*→	Mechanisms for Adaptation i) Intentional redesign by non-end users ii) Redesign by end users iii) Learning by doing iv) Learning by using
5. **Technology in Widespread Production & Use Stock**	
e) Retirement Flow →	Mechanisms for Retirement i) Risk assessment ii) Decreased demand iii) Relative cost or performance iv) Revealed harms at scale
6. **Obsolete and Retired Technology Stock**	

*Early Adoption and Adaptation may take place at multiple points, but are listed only once here for the sake of clarity. A more complex model reflecting non-linear processes is illustrated in Figure 1.

Dynamic systems are conceptualized as consisting of stocks and flows. Flows between stocks are mediated by mechanisms (listed in Table 2), with the flow of a technology from one stock to another depending on the conditions of the technology in the stock and the rules governing the functioning of mechanisms. The conditions surrounding a technology in a given stock are a function of the technology itself and its context (we will later refer to these conditions as "socio-technical conditions"). Stocks are tangible and countable. They could include the number of possible technologies available to an end user to solve a certain problem. The actual quantity of technologies in a stock changes over time via flows in and out. These flows might include technologies that go from being prototypes in the stock of feasible technologies [#3 in Table 2], to those that are implemented by a set of early adopters (technologies in limited production & use [#4 in Table 2]. Stocks generally have inflows (e.g., the invention flows [#1 in Table 2] and adaptation flows [#6 in Table 2] feed into the invention stock) and outflows (e.g., selection and retirement flows, which take technologies outside of the invention stock). The level of a stock at any given time is determined by its initial value, the rate of both incoming and outgoing flows, and the mechanisms and socio-technical conditions governing those flows.[24,25] We are interested in the dynamic relationships in the innovation system, in terms of the ways that an individual technology flows and evolves between stocks, and understanding the conditions that impact the rates of those flows —including those that inhibit as well as those that facilitate innovation and access.

We define socio-technical conditions (STCs) of a technology as those properties that we found to be relevant for explaining the extent to which different technologies were able to flow and evolve between stocks. Our list of STC's was developed inductively from the eighteen cases and using a literature review. When STCs take particular forms (described in Part 3.3), they can inhibit the flow of the technology between stocks, in which case we refer to them as inhibiting STCs. We use the term "socio-technical" to encompass both technological aspects (characteristics that apply to the technology no matter where it will be used), but also the social practices and context that relate to the technology (who selects the technology, the local infrastructure, the capacity of users, etc.). The inhibiting STCs may inhibit particular mechanisms that would move technologies from one stock to another. The mechanisms governing the seven flows were also derived through a synthesis of the literature and inductively from the cases, and are described in Part 3.2.

For this project, our questions of interest are: (1) what STCs affect the flow of technologies through the innovation system, and (2) how to diagnose systemic weaknesses where transnational actors or institutions could intervene to strengthen the overall system?

3.1 Knowledge, Invention, and Technology Stocks

The six stocks in the conceptual model of innovation are defined as follows:

1. **Knowledge stock:** This stock refers to all generated knowledge that is relevant for (but does not describe) a particular application, up to a particular date or time-point. This includes knowledge codified in academic papers, as well as theories, and databases, and other forms of knowledge that may not be codified (e.,g., knowledge in the minds of inventors about intuitive physical relationships). The knowledge stock can be increased through **basic research** and other more **experiential processes of knowledge advancement**.[26] For a particular location, the knowledge stock can increase by searching for knowledge already available in other places.

2. **Invention stock:** An invention is a solution resulting from the synthesis of understanding of a need and knowledge about the technical means with which the need, want, or demand may be

[24] A common analogy is a stock of water in a bathtub. The level of water in the tub will depend on the flow rate of that water that enters through the tap, and the flow that exits through the drain. The processes governing the flows (and thus, together with the starting amount of water in the tub, the ultimate stock) in the simplest case, relate to the size of the inflow and outflow pipes, and perhaps factors determining the pressure on the input flow.
[25] Meadows, D.H. (2008). Thinking in Systems: A Primer. Chelsea Green Publishing, 17–20.
[26] Basic research and experiential processes of knowledge advancement are processes of innovation, parallel to the processes described in Section 3.2 below.

met.[27] This stock differs from the Knowledge stock in that new information was generated to translate the existing knowledge into a technology – that is, "knowledge of how to fulfill certain human purposes in a specifiable and reproducible way."[28]

3. **Feasible technology stock:** This stock refers to technologies that may be produced. It differs from the Invention stock in that they are inventions that have not been ruled out, for example by regulations or prohibitive cost, nor have progressed far enough through development to be considered possible to reproduce at larger scales (i.e., beyond pilot scales, or prototype levels).

4. **Technologies in limited production & use stock:** The stock of technologies in limited production and use is made up of technologies that, while in use, are not yet fullfilling their potential. They may have been tried in a few cases through subsidy programs, or early movers, but are not yet close to meeting all the relevant potential demand. These technologies may be newer, or may not be disseminated widely beyond technical, geographical, or socio-economic niches.

5. **Technologies in widespread production & use stock:** The stock of technologies in widespread production and use is made up of technologies that have expanded spatially to many markets, thus fullfilling a significant proportion of needs. An important dimension of widespread production and use is the capacity for widespread technologies to persist over time, allowing for actors to sustain their production and use of the technology for greater benefit. Separating stocks of technologies in "limited" versus "widespread" production and use gives us a more nuanced understanding of the factors that affect access to technologies by different populations.

6. **Obsolete and retired technology stock:** These are inventions or technologies that are no longer widely used or deemed obsolete for meeting the needs they were meant to address or any other used they may have had.

3.2 Mechanisms Facilitating Flows Between Stocks

Technologies move between stocks non-linearly via seven *interconnected and interacting* flows: invention, selection, production, early adoption, widespread use, adaptation, and retirement. These flows between stocks are mediated by a series of mechanisms. We separate the different processes for analytic clarity, but emphasize that as with any complex dynamic system, they may overlap, occur

[27] Utterback, J.M. (1971). The Process of Technological Innovation Within the Firm. Academy of Management Journal: 75–88. [And:] Schmookler, J. (1966). Invention and Economic Growth. Cambridge, MA: Harvard University Press. [And:] Marquis, D.G. (1969). A Project Team Plus PERT Equals Success. Or Does It. Innovation 1(3): 28–37.
[28] Brooks, H. (1980). Technology, Evolution, and Purpose. Daedalus 109(1): 65–81.

simultaneously or sequentially, and be connected to each other via complex feedback loops. [29] A given technology may loop through different stocks in a number of ways, and indeed may never go through all of them.[30]

Below, we describe each flow and the underlying mechanisms that can enable them. An understanding of the flows and underlying mechanisms becomes particularly important when demand, or ability or willingness to pay for a particular need are not sufficiently large to attract enough interest from different types of investors and entrepreneurs (public or private). This is not unusual for technologies that some see as having the potential to contribute to mitigating environmental externalities that are not priced, or for technologies where demand pull is weak or fragmented because end-users are poor. It is worth mentioning, however, that even technologies for which demand is in theory sufficient to attract investment may not be widely used if regulations or other major infrastructure barriers filter out (or negatively select) those technologies. We now turn to describing the flows connecting stocks and the mechanisms enabling them those flows.

1. **Invention flow:** The invention flow involves developing the means to meet a need through the use of existing knowledge. The mechanisms facilitating the invention flow link the knowledge stock to the invention stock, or amplify the invention stock from within. A classic mechanism is **goal-oriented search,** motivated by users or policy incentives, when existing options are not satisfactory. Invention can also begin with experimentation with a phenomenon or effect, during the course of which an application is **accidently discovered**. A third mechanism is the **repurposing** of an invention for a new field of use distinct from the field of use the invention was developed for. Through repurposing of an existing invention, the invention stock is expanded by allowing for technologies to address more needs. This mechanism involves little change to the technology itself, unlike re-design (discussed under the adaptation process), but together with re-design is what is sometimes referred to as "technology spillovers" in the literature. Translating base principles into physical reality often requires the creation of suitable working parts and supporting technologies.[31] Invention also includes the invention of new practices or operations (e.g., new management of financing practices for getting water treatment to remote places).

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[29] Edquist, C., and Johnson, B. (1997). Institution and organizations in systems of innovation. In: C. Edquist (Ed). (2007). Systems of Innovation: Technologies, Institutions and Organization. London: Pinter, 41–60. [And:] Lundvall, B. National innovation systems-concept and development tool. Industrial Innovations 14: 95–119.

[30] For example, an invention may move through production and initial adoption after an NGO has decided to provide that invention to a particular population, however wide spread use of the new technology may prove difficult without support from local governments. Or a country may decide to rule out GMO foods in favor of non-GMO products, preventing GMO-food production through the regulation mechanism. Cultural or geographic differences between a place where a particular cookstove is used and a place where it could be used may lead technology entrepreneurs or local experts to adapt the technology. A technology like mobile applications for sanitation may become widely used once the complementary technologies, including telecommunications infrastructure make the benefits worthwhile.

[31] Arthur, W.B. (2007). The Structure of Invention. Research Policy 36(2): 274–287.

2. **Selection flow**: Selection can involve surveying the landscape of options and making choices about which technologies to promote or invest in, thereby moving a technology from the invention stock to the feasible technology stock. Because, by nature, selection involves the choice of one technology over others, it also encompasses the act of "promotion" – that is, of championing a particular technological innovation. Few technologies, if any, are without drawbacks and the selection of one technology over another often creates winners and losers, making the selection of technology frequently a political process. The mechanisms enabling the selection process involve actively or passively choosing among the universe of available technologies (the invention stock) to meet a particular purpose in a particular context. Examples of selection mechanisms include **selection by users; selection by policy (e.g., regulations, national objectives); and selection by agents who choose technologies on behalf of principals (users)**. While selection by users is frequently active, (e.g., a consumer purchasing a type of water filter), selection can also be diffuse and unintentional. Laws and regulations may indirectly favor one technology over others in ways that may not have been initially apparent to policymakers (e.g., the failure to change the broader policy framework results in a preference towards the status quo over a new technology) Governments are often criticized for directly or indirectly "picking winners" via regulatory, financing and policy regimes. Selection may also take place by agents, for example, when venture capital firms choose a technology for investment, or NGOs promote a particular technology to solve a particular problem.

3. **Production flow:** The production flow moves tangible and intangible technologies from the stock of feasible technologies to the stocks of technologies in limited or widespread production or use. For tangible technologies, mechanisms enabling production involve **manufacturing**, in addition to the **codification and dissemination** of manufacturing practices; for intangible technologies, such as practices, the mechanisms that enable production include the **codification and dissemination** of the practice (e.g., the training of experts adept in the practice with the ability to support other users in initial adoption). Production may also require the creation of infrastructure. This can include developing supply chains, or the construction of factories or other supporting structures, such as seen in wastewater reuse, which requires the laying of significant pipework. For some technologies, such as large-scale carbon capture and storage systems, the mechanisms for production are largely synonymous with those of initial adoption, while for others, such as cookstoves, they are distinct and face different barriers. Production processes can also be enhanced by **network effects** that allow for more effective production by capturing synergies between several producing organizations.

4. **Initial adoption flow:** Initial adoption is the initial use of a technology by a subset of potential users (sometimes referred to as "early adopters"), and moves a technology from the stock of feasible technologies to those in limited production and use. The process of initial adoption can be facilitated by mechanisms to **market** the technology (e.g., through advertising campaigns, or public or NGO led efforts to promote a technology), and to make it less costly or risky, such as temporary **relative price changes** (e.g., subsidies, discounts), or providing **benefits for early**

adopters (e.g., increased economic output or efficiency, reputational effects), or **laws and regulations** that promote investment in new technologies (e.g., cap and trade schemes). Initial adoption is also mediated by **behavioral tendencies or cultural tendencies**, which can promote or hinder the adoption process. **Access to information** (e.g., through pamphlets, technology expos and increasingly information and communication technologies such as cell phones) is another channel that influences initial adoption. Initial adoption can also be prompted by disruptive events that catalyze attention and enthusiasm for a particular technology or practice, by changing the benefits for adopters. An example of these disruptive events would be the long drought (1997–2010) in Australia that increased interest in wastewater reuse technologies and jumpstarted adoption.

5. **Widespread use flow**: Widespread use includes the processes by which technologies move from limited use to being adopted in a sustained manner or on a wide scale by a significant proportion of potential end-users. Importantly, mechanisms enabling the widespread use process can have a spatial and/or a temporal dimension, depending on the technology and need being addressed. This group of mechanisms encompasses all aspects of access, dissemination, and uptake of a technology. Similar to initial adoption, widespread use can be facilitated by the mechanisms of: **marketing, relative price changes, benefits to adopters, behavioral or cultural tendencies**, and **access to information**. In addition, widespread use can also be facilitated by positive feedback from **network effects** (e.g., for example, the widespread adoption of residential solar panels typically accelerates due to peer-effects, and the widespread use of the apps monitoring water sanitation would likely be accelerated if a network of trained professionals decreased the full costs of adoption).

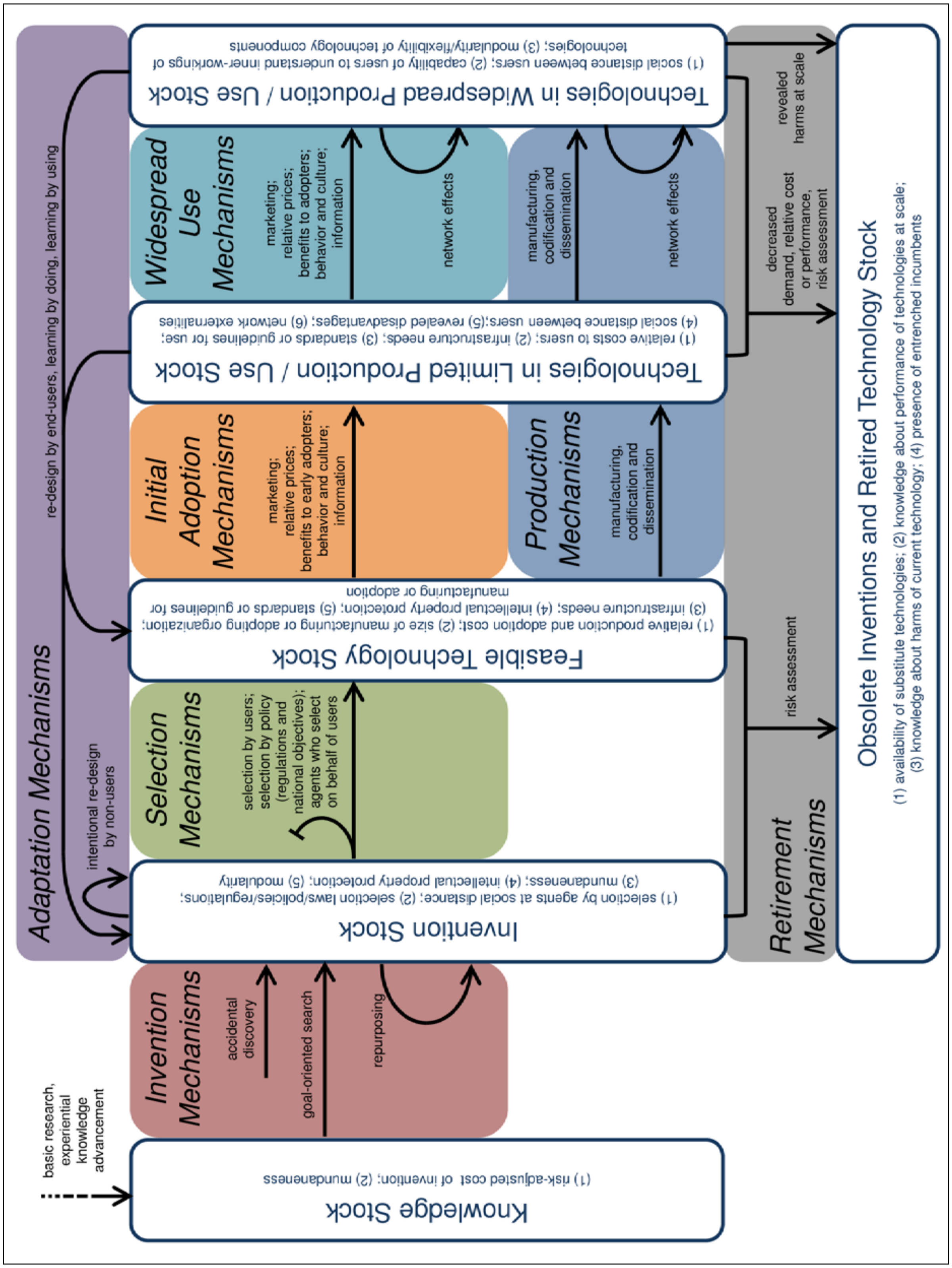
6. **Adaptation flow:** The process of adaptation involves making adjustments to a technology and/or to its complementary technologies for use in contexts distinct from that in which the technology was initially invented, selected, or adopted. Many technologies are not immediately suitable for use in the contexts in which they may be needed or adopted, and the process of adaptation can pose many challenges, even after decisions around adoption have taken place. These other contexts include new geographic/spatial (e.g., soil types, rainfall patterns, configurations of industrial plants, available inputs), social/cultural (e.g., labor practices, acceptable uses, norms, political acceptability), regulatory, and market segment conditions. Adaptation includes both **re-design by non-users,** which operates on the invention stock by responding to identified shortcomings of the technology or user needs and **re-design by end-users**, which operates on technologies in limited or widespread production and use by optimizing the benefits that a technology may provide in a particular context. The latter type of re-design includes **learning by using** (adjusting practices of use) and **learning by doing** (adjusting practices of production and stimulating follow-on incremental invention). The line

between adaptation and invention is necessarily grey[32], as the difference between incremental (adaptation) vs. significant changes (invention or re-invention) to a technology is not always clear. Adaptation mechanisms demonstrate the non-linearity of the innovation system as they can move a technology within and between multiple stocks: invention, technologies in limited production and use, and technologies in widespread production and use.

7. **Retirement flow**: Technologies do not generally provide permanent solutions to problems, but rather eventually become relatively less effective or useful. Retirement mechanisms can move a technology out of multiple stocks: invention, feasible technology, and technologies in limited or widespread use. [33] Technologies may be retired from the technologies in limited production/use stock and from the technologies in widespread production/use stock because new technologies make the existing technology obsolete in its **relative performance** or **relative cost** ("performance" and "costs" refer to all economic, political, social, and risk-related costs and performance). Technologies can also be retired from both stocks due to absolute **decreased demand** for the technology. Finally, new knowledge about technologies, previously deemed feasible, can also lead to restricted use or retirement due to new **risk assessments**. Technologies can be retired from the widespread production/use stock due to **revealed harms at scale,** which can deem technologies to be no longer desirable or at least subject to restrictions. It is also important to note that sometimes it is necessary for the incumbent technology to be retired before a new technology becomes widespread, especially in the case of capital-intensive technologies with high capital costs.

[32] For example, we distinguish adaptation at this point in the innovation process from those cases where an inventor selects or adapts an existing technology for a new purpose. We refer to those cases as repurposing—also referred to as spillovers in other contexts—and classify them under invention.
[33] Gallagher, K.S., Grubler, A., Kuhl, L., Nemet, G., and Wilson, C. (2012). The Energy Technology Innovation System. Annual Review of Environment and Resources 37: 6.1–6.26.

Figure 1. Conceptual Model of the Innovation System



Part 4. Comparative Case Analysis: Framework for diagnosing the innovation system through the lens of socio-technical conditions

This section discusses how we utilized the conceptual framework as a diagnostic tool for understanding the key challenges facing the innovation system for a particular technology. In utilizing a common framework to analyze the eighteen cases, we found it useful to characterize the cases according to STCs (which incorporate characteristics of the technology and the context in which the technology is to be used). Through this characterization, we were able to correlate certain combinations of STC "values" and mechanisms with the strength or weakness of particular flows between different stocks—we call these "inhibiting conditions." This enables us to understand the conditions under which technologies are able to flow between stocks, and conversely, the conditions under which this flow is inhibited.

Our analysis of the cases is based on the relationship between the STCs of a technology in a particular stock of the innovation system, [34] and the mechanisms that govern the flow of the technology from stock to stock.[35] We hypothesize that these STCs determine the type of mechanisms applied to move a technology between the stocks and the probability that a technology will flow through a particular mechanism. For example, technologies that share STCs in the limited production/use stock, tend to flow out of the stock through the same adaptation mechanisms. The STCs that we found to help explain the type and strength of mechanisms that govern the flows of technologies across stocks are detailed in Table 3.

While our investigation of the STCs was to a large extent qualitative, we were nevertheless able to assign a binary classification of technologies to either "high" or "low" levels of each STC, facilitating comparisons across cases. The evaluation of STCs and mechanisms suggested in our framework can help identify potential interventions by transnational actors or institutions to stimulate different mechanisms to promote innovation, as discussed in Part 5. Table 3, below, summarizes the conditions under which movement between stocks was inhibited. These conditions can be made up of up to three elements: a particular STC of a technology in the given stock that is independent of context, a particular STC that depends on context (which could determine which mechanisms apply or do not apply), and the mechanisms that enable the technology to flow to another stock. In some cases, a particular STC acts as an inhibitor, regardless of mechanism or the underlying context. In other cases, it was the combination of STC and mechanism that was problematic. While some of the connections are almost tautological, identifying the conditions that can disable the flows between stocks can help systematically diagnose both ex-ante and ex-post some of the bottlenecks faced by different technologies. In turn, this can help identify policy interventions to address these bottlenecks.

[34] It should be noted that there were some characteristics that were important for more than one stock.

[35] We initially tried to identify STCs independent of specific stocks common to a group of cases, but we found no analytic traction in this approach.

Table 3. STCs that are likely to inhibit flows between stocks

Flows between Stocks	Conditions that Inhibit Flows	Rationale
1. Knowledge Stock to Invention Stock (Invention Flow)	Technologies that have a high risk-adjusted cost of invention when the invention mechanism is goal-oriented search	More risky invention lowers the returns to invention investments
	Technologies that are highly "mundane" when the invention mechanism is goal-oriented search	Mundane technologies attract less invention investment
2. Invention Stock to Feasible Technology Stock (Selection Flow)	Technologies for which the selection mechanism is by agents with high social distance to principals	Entrepreneurs and donors are more likely to select inappropriate technologies when at greater distance from users
	Technologies where the laws, policies or regulations are inapt for sustainable development when the selection mechanism is policy	Selection may "filter out" more appropriate technologies
	Technologies that are highly "mundane" when the selection mechanism is by agents	Entrepreneurs and donors are likely to favor more fashionable technologies
	Technologies with low potential return on investment (may be absence of intellectual property rights or resource-poor end-users), when the selection mechanism is by agents	Entrepreneurs favor technologies on which they are likely to earn an attractive return on investment, which may be more likely with exclusive commercialization rights and/or a potential market of well-resourced end-users
	Technologies that have a low level of modularity or flexibility that require re-design by non-users and/or re-design by end-users as a precursor to selection mechanisms	Non-users and users alike will be less likely to adapt technologies that are complexly integrated
3. Feasible Technology Stock to Technologies in Limited Production/ Use Stock (Production and Initial Adoption Flow)	Technologies that have high relative prices (linked to costs of production or adoption) as compared to incumbents or purchasing power of users when the mechanism for initial adoption/production is relative price	High relative costs of production/adoption increase relative prices in competitive markets
	Technologies where the size of organization manufacturing and/or	Small organizations may have difficulty acquiring information about production

Flows between Stocks	Conditions that Inhibit Flows	Rationale
	adopting, is small, and the mechanism for initial adoption/production is information	and adoption
	Technologies that have high infrastructure needs (human and physical) in which the mechanisms of initial adoption/production are marketing and/or relative prices	Infrastructure dependence makes marketing more challenging and could result in higher prices due to large transportation costs
	Technologies with intellectual property protection when producers use it to extract monopoly rents, and the adoption mechanism is relative prices	Intellectual property protection can increase prices above costs by enabling monopoly rents.
	Technologies where there is an absence of standards or guidelines for manufacturing and/or adoption when the mechanism of initial adoption/production is the benefits to early adopters	In the absence of standards, poor performance is more likely, resulting in lower benefits to early adopters
4. Technologies in Limited Production/Use Stock to Technologies in Widespread Use (Widespread Use Flow)	Technologies with high relative prices (linked to costs of production, adoption, or IP) as compared to incumbents or purchasing power of users when the mechanism of widespread adoption is relative price	High relative costs of production/adoption, or IP-enabled monopolies increase relative prices
	Technologies with high infrastructure needs (human and physical) when the mechanism of widespread adoption is either marketing and/or relative prices	Infrastructure dependence makes marketing more challenging and could result in higher prices due to large transportation costs
	Technologies where there is an absence of standards or guidelines for manufacturing and/or adoption when the mechanism of initial adoption/production is the benefits to adopters	In the absence of standards, poor performance is more likely, resulting in lower benefits to adopters
	Technologies with a high social distance between the original user or promoter of a technology and new users when the mechanism of widespread adoption is marketing and/or relative prices	Technologies in limited use require greater marketing efforts or greater differences in relative prices to reach users at far social distance
	Technologies with revealed disadvantages when mechanism of widespread adoption is relative	The initial production and use of a technology may reveal new disadvantages that were previously unapparent, hindering

Flows between Stocks	Conditions that Inhibit Flows	Rationale
	prices, marketing and/or access to information	the ability of relative prices, marketing, and information to facilitate more widespread adoption
	Technologies with high network externalities, when mechanism of widespread adoption is relative prices, marketing and/or network effects	In the presence of network externalities, prices will be higher for small-scale production and use, marketing will be more difficult, and network effects will not be slow to encourage production and use
5. Technologies in Widespread Production/Use Stock to Feasible Technology Stock and/or Invention Stock (Adaptation Flow)	Technologies with high social distance between the original user of a technology and new users mechanism of adaptation is re-design by end users	End-users are less likely to effectively re-design technologies for users at far social distances
	Technologies in situations where there is low capability of users to understand inner-workings of technologies when the mechanism of adaptation is re-design by end users	End-users with low capability to understand how technologies work will be less likely to re-design technologies
	Technologies with low modularity/flexibility of the technology's components when the adaptation mechanism is re-design	Technologies that are less modular or flexible are less amenable to re-design
6. From all other stocks to Obsolete and Retired Technology Stock (Retirement Flow)	Absence of substitute technologies when the retirement mechanism is decreased demand	In the absence of substitute technologies, existing technologies in limited or widespread use are unlikely to be retired
	Technologies for which there is limited knowledge about performance when the retirement mechanism is revealed harms of technologies at scale	In the absence of knowledge about the performance of technologies at scale, it is unlikely that harms only realised at scale will lead to retirement of technologies in widespread production/use
	Technologies for which there is limited knowledge about harms of current technology when the retirement mechanism is risk assessment.	In the absence of sufficient knowledge of the harms or adverse side effects of feasible technologies, it is unlikely that risk assessment will inspire action to make technologies obsolete
	Technologies that are incumbents with low relative costs compared to other technologies, and/or with political support for the status quo, when the mechanism of retirement is decreases in demand	Entrenched incumbent technologies are locked-in to socio-technical systems, making decreased demand and disadvantageous relative costs less likely to drive retirement of technologies in limited or widespread production/use.

We now turn to explaining Table 3 above in more detail, including some specific examples from the cases underpinning the analysis.

4.1 Knowledge Stock: STCs inhibiting the invention flow

Two STCs that can contribute to inhibiting the invention flow are **high risk-adjusted cost of invention** and a **highly "mundane"** (as opposed to "fashionable" or "sexy") technology. In our case analysis we observed a wide diversity in the types of actors, resources and interventions that were involved in the process of invention. In part this diversity depended on the risk-adjusted cost of invention (either high cost for a given risk of invention or high risk for a given cost of invention); greater risk increases costs to firms investing in invention. This diversity also depended on the whether a technology was considered mundane, which refers to whether a technology is perceived to be of compelling interest to key actors and technology champions.

Technologies associated with a high risk of invention and technologies that are highly mundane (which can be context dependent) are often associated with insufficient resources in invention. In particular, these types of technologies usually experience weaker support for goal-oriented search in invention. In some cases this could be driven by the low availability of funding from investors, firms, or grant-making agencies to engage in certain types of research. For academic researchers, it may be too risky to work in an area with little grant funding available or that may not be publishable in journals recognized in their particular disciplines. The ad hoc nature of invention for technologies that do not have large or dense markets results in invention efforts that favor technologies that are fashionable or perceived to be as up-and-coming over other more mundane (and perhaps more appropriate) technology alternatives.

Our major finding for technologies in the knowledge stock is that technologies with high risk of invention or highly mundane technologies may face challenges during the process of invention. Both types of technologies are receiving support in an ad hoc fashion, and likely are underfunded relative to their social value. We also found that the types of interventions that are enabling some new inventions (and could enable more if they were supported more systematically) for technologies with high invention cost intensity are different from those that support invention for low invention cost technologies; this is discussed in more detail in Part 5.

4.2 Invention Stock: STCs inhibiting the selection and adaptation flows

The key STCs associated with lower selection and adaptation flows are whether the technologies are selected **by agents with high social distance to principals** (i.e., users), selected **by laws, policies or regulations inapt for sustainable development**, **highly mundane technologies**, **low potential return on investment**, and **technologies with a low level of modularity**.

When agents are at a greater social distance from users, they tend to have insufficient knowledge of the needs of the users, and therefore, there is a greater likelihood of inappropriate selection compared to when a technology is selected from the invention stock by users themselves. Non-profit organizations supplying technologies without consulting the user communities are examples of selection by such agents. The cookstove and ceramic filter cases illustrate how selection can occur by actors who are not the end-users of the technology and lead to suboptimal technologies offered to users. Laws, incentives, regulations, and national objectives may significantly limit what technologies are legally feasible to meet particular needs. The wastewater reuse case highlights the challenge of laws and regulations that act as "selectors," which perpetuate the status quo and facilitate technology path dependency.

Inventions that offer little to no return on investment are not likely to be selected by entrepreneurs or investors, who will seek more commercially attractive opportunities. The existence of intellectual property rights on the invention can change this calculation by enabling rights-holders to capture monopoly rents, but only when end-users have adequate purchasing power. Similar to invention, technologies that are mundane may be overlooked by selecting agents, who may favor a technology that is more current or fashionable, despite what may be of greatest benefit to the end-user. Finally, inventions that are not modular or flexible are more difficult to re-design by non-users. In several of the case studies, there were examples driven by the end-users themselves, including the Higg index, and the System of Rice Intensification cases. In some of these cases, users directly selected technologies that could be considered "mundane." What is not clear is whether the characteristic of "sexy" vs. "mundane" is differentially important for selection via agents or via users. In addition, the SRI case demonstrated that there are also often barriers to inventions bubbling up from "non-expert" end users, especially if those inventions are very different to solutions developed by expert communities.

4.3 Feasible Technology Stock: STCs inhibiting the initial adoption and adaptation flows

We observed that technologies with several STCs are less likely to flow out of the feasible technology stock through production and initial adoption[36]: **high relative prices, small size of the organization manufacturing and/or adopting, high infrastructure needs (human and physical), intellectual property protection when used to enable higher prices, and the absence of standards or guidelines for manufacturing and/or adoption.** By high relative prices, we refer to prices relative to the purchasing power of users or to the prices of incumbent technologies. Prices may be high because of production or adoption costs, or because of other attributes of the technology such as patent status, which allow sellers to charge prices above costs of production. This challenge was illustrated by the case of Ready-to-use Therapeutic Food (RUTF), in which some producers used patents to keep competition out of the market, which led to higher prices charged to donors providing food in emergency conditions, and the case of cancer drugs in

[36] The degree to which production and adoption processes are separated varies across technologies. Production and adoption largely overlap in technologies like geothermal power and water reuse, in which the geographic location of the production of the technology (the construction of the geothermal and water reuse facilities) as well as the actors involved, and its adoption (to generate power and water) are the same. In contrast, in technologies like cookstoves, ceramic water filters, and vaccines or medicines, production and adoption have different actors and are often separated in time and space. For example, in the cookstove case, parts were manufactured in India, and assembled locally in Darfur before they were distributed to users.

India, in which the prices charged by firms far exceeded the capacity of most Indians or the national health system to pay. Even in the absence of patents, many of the technologies considered in the cases were generally more expensive than incumbents since they have not benefitted from processes that lower costs over time, including economies of scale, development of stable supply chains, and learning by doing. The relative prices and benefits to early adopters mechanisms will not work well for technologies with high prices relative to incumbents or users' ability to pay.

The carbon capture and storage case and the geothermal energy case are examples where producers and/or adopters were large organizations. Cases where smaller actors were involved with production and initial adoption include cookstoves, ceramic filters, and the System of Rice Intensification. The mWASH, RUTF and industrial symbiosis[37] cases show that for some technologies there are different sizes and types of adopters; for example, the ultimate adopter for mWASH could be a multi-lateral organization interested in improving monitoring and evaluation, a utility interested in enhancing its operational efficiency, or an individual water user seeking information about his/her water supply. In many technologies, the size of the producing firm is different from the size of the adopter, or the level of standardization in production may be different from the level of standardization in adoption. For example, in the cookstoves case, the cookstoves were mass produced in India to high specifications and by a qualified large firm, but adopted in Darfur by individuals and with less codification in terms of their conditions of use. Large organizations may have the expertise to search and handle more complex information that perhaps smaller organizations and individuals cannot process or absorb.

Our cases highlighted two important types of supporting infrastructures that are important in production and initial adoption. The first is physical infrastructure (manufacturing facilities, roads, distribution networks, etc…), and the second is human infrastructure (capacity of producers and/or users to manufacture, operate, and repair).

Technologies with high physical infrastructure needs (e.g., manufacturing facilities, roads, power grid, parts for repair) are also less likely to have beneficial relative prices, since investments to develop the infrastructure may make them harder to compete in costs with incumbents. In cases that involved production in areas with poor physical infrastructures, like waste water reuse, and ceramic pot filters, problems in production led to problems with widespread adoption. Ceramic pot filters tend to be manufactured locally not only because they are fragile, but because they are seen as a way to promote local economic development and because local manufacturing leads to products that are well-adapted to users' needs. Moreover, without good roads, it can be difficult to deliver fragile ceramic pot filters to remote villages. Technologies with high human infrastructure needs[38] (e.g., capacity of producers to manufacture, operate, or repair) may require the provision of additional

[37] Industrial symbiosis is a layered case. IS programs studied were codified and adopted by government actors and/or associations of co-located industries. But success required convincing a critical mass of smaller firms to participate in a second part of the initial adoption stage.
[38] Jimenez, E. (1994). Human and Physical Infrastructure: Public Investment and Pricing Policies in Developing Countries, Volume 1. World Bank.

information and/or marketing (such as extension services), making it harder for the technology to go through production and initial adoption (e.g., SRI case). The need for a technology to access human infrastructures may also, in some cases, increase the price of the technology compared to other alternatives in cases where these resources are absent or limited. When manufacturers or adopters are small firms or individual users, these adopters may find it challenging, if not impossible, to invest in technologies with high production costs, high infrastructure needs, and little availability of standards and guidelines. In that sense, this STC is associated with reduced effectiveness of all the mechanisms for production and initial adoption: perceived net benefits, codification, and information provision**.** This STC of manufacture or adoption by small firms or users interacts with others, particularly the need for guidelines, support and codification of STCs.

Intellectual property, such as patents, can allow producers to set prices above production costs when there is some purchasing power, which can limit the adoption of a technology. While intellectual property can inhibit adoption in some cases, it can enable selection in others, illustrating the well-known social tradeoff of IP protection between incentivizing the creation of new technologies through monopoly rents that limit diffusion and creating barriers to access especially by poor and vulnerable members of society.

Finally, technologies with little availability of standards or guidelines are those that are not accompanied by a system that allows producers or manufacturers to produce them in a replicable and successful manner. In cases in which production did not have codified, well-communicated, and enforced quality standards and guidelines, such as ceramic pot water filters, production again suffered. In the case of malaria medicines, products that did not meet international regulatory standards were excluded from the global subsidy, which generated local political opposition to the subsidy. In the SRI case, we saw that the flexibility of SRI methods combined with the unconventional source of the invention led many actors in the global innovation system to initially ignore or even mistrust the technology, which resulted in an under-investment in research by the agriculture community.

These STCs were associated with clear differences in successful intervention strategies at this juncture in the innovation system. For example, the possible interventions that can help promote adoption in cases in which the adopting actor was a large organization (with significant capabilities to review options, acquire expertise, and analyze tradeoffs) were different from those in cases in which the adopting actor was small, including an individual (with less time and access to information to search for the most appropriate technologies). We found that for technologies where the adopting actor was small, system interventions to reduce information costs and risks for smaller-scale end-users could be carried out by transnational actors.

4.4 Technologies in Limited Production/Use Stock: STCs inhibiting the widespread production/use and adaptation flows

The STCs that inhibit the flow out of the Technologies in Limited Production/Use stock are: **high relative prices**, **high infrastructure needs, absence of standards and guidelines for use, high social distance between original users/promoters and new users, revealed disadvantages,** and **technologies that benefit from network externalities**. We observed a lower likelihood of a successful widespread production/use for technologies with high relative prices compared to the perceived net benefits. In some cases, technologies were more expensive because they added costs and/or other risks to the incumbents, (e.g., like CCS, which can only be cost-competitive if environmental externalities of burning fossil fuels from stationary plants are priced in or if the CO_2 can be profitably used for processes like enhanced-oil recovery). In other cases, technologies were simply relatively costly to use compared to the ability of end-users to pay – this was a major justification for the global subsidy on malaria drugs (AMFm) and for small farmers (despite the relative inexpensive nature of drip irrigation, their ability to pay without significant state support is limited). In yet other cases, technologies were costly but have the potential to be improved through economies of scale or learning-by-doing (this may be the case with cookstoves, and Higg index).

We observed that technologies with high infrastructure needs (physical or human), and technologies with little availability of standards or guidelines for use faced difficulties in the innovation process. These technologies tend to have high relative prices, making it harder to move from early adoption to widespread use. Just like in initial adoption, this is also a challenge for technologies adopted by small-scale users, which are less likely to be able to benefit from information if it is not produced in the right form.

Social distance between the promoter or initial user of the technology and new users can impact the further widespread use of the technology, due to lack of strong feedback loops between promoters and adopters. For example, the promotion of cassava bread in Nigeria by presidential regulation resulted in a backlash from the population that preferred bread made from wheat flour even though it was more expensive. Thus the distance between the promoter of the technology and users led to inappropriate selection and the technology not being more widely used.

Technologies in limited production and use may reveal previously unapparent disadvantages through initial experience in production and use with the technology. These new disadvantages can be compounded by social distance and lower the effectiveness of relative price, marketing, and access to information mechanisms. For example, when the World Bank and Grameen Shakti selected solar photovoltaics for household electrification, small businesses that required greater electricity needs than the technology could offer (e.g., small agricultural and industrial) were at a disadvantage because these users would have to wait longer than they otherwise would have for grid connections.

Technologies that benefit from network externalities to become desirable or cost effective create disincentives for early movers, and encourage free riding by later adopters, which may slow or impede their progress from limited to wider use. For these technologies, once they reach a "critical mass" of users, they have the potential to expand very rapidly and widely. An example of this is the solar PV case, which saw disadvantages for early adopters of micro-grid configurations (multi-houehold configurations where later adopters could free-ride on the earlier higher costs, impeding widespread adoption), while individual solar home systems did not share this barrier.

4.5 Technologies in Widespread Production/Use: STCs inhibiting the adaptation flow

There are three key STCs of the technologies in widespread production/use stock that inhibit adaptation flows: **high social distance between the original user of a technology and new users**, **low capability of users to understand the inner-workings of technologies,** and **low modularity/flexibility of the technology's components**. The distance between original and new users can extend over spatial, socio-cultural, regulatory, or market segments. High distances between original and new users indicate cases in which technologies needed to be significantly adapted to radically new users, geographies, or cultures. This is in contrast to technologies that are only used in similar ways by similar users. The "distance" to adaptation can also include the merging of two very distinct sectors, such as the traditional IT sector and the traditional development sector, each of which have very different institutional cultures. In situations where the distance between original users and newer user groups are high, and the ability of new users to adapt these technologies to their contexts are low, technologies are less likely to be successfully adapted**.** This can limit the scope of usage, and may negatively impact access for certain groups. An example of this high social distance can be seen in the case of SRI, in which without extension services, farmers have difficulty accessing information about SRI, accepting the risks of initial adoption of a *locally* untested technology, and implementing a complex set of methods that make up the package of practices of SRI.

The ability of users to understand the principles behind the technologies they use affects the likelihood that they will tinker with and improve these technologies through adaptation mechanisms. In the case of SRI in Bihar, farmers understand both scientific and more humanistic principles (such as the needs to treat plants carefully as living creatures) of the methodology which helps them incorporate SRI into their practices and engage in tinkering and experimentation with the method based on these principles.

In addition, technologies with low modularity or flexibility are less amenable to adaptation, since the entire technology must be changed rather than only the modular components that might render it more useful in a new context. Low modularity may be physical, but it may also be informational (as with software) or legal (as with patents that impede adaptation of a product). Technologies with high distances between new and original users or with users with low capability to adapt are unlikely to benefit from the mechanism of re-design by end-user or original producer. In those cases, third-party adaptation, possibly through transnational intervention, may be needed to realize the full promise of a technology.

We found that for technologies with a large distance from original users to new users, potentially effective system interventions include efforts to build capacity or to finance adaptation work elsewhere (e.g., Western academic centers) for subsequent import. We used this characteristic to separate cases such as cookstoves, drip irrigation systems, ceramic pot filters, and mWASH apps, which often require a significant level of adaptation, from solar panels and cancer drugs, which require attention to distribution methods, financing, and cultural context but relatively low need to adapt the artifact itself (low). In the mWASH example, while there are an increasing number of mobile applications, they still require financial resources to adapt properly—training, investment, and monitoring to make them effective in the field.

We also found the capacity of end-users to adapt technologies (which depends both on the knowledge of users as well as the technology itself) allowed us to differentiate between cases like SRI or mWASH in which users did not have the knowledge to adapt the technologies themselves and industrial symbiosis in which they did. This allows the analysis to identify when interventions aimed at providing general skills to the users to help them adapt the technology themselves may be more effective than providing specific support for adaptation and then the dissemination of the adapted technology.

4.6 Obsolete and Retired Technology Stock: STCs inhibiting the retirement flows from the different stocks

The key STCs that can inhibit the flow of technologies into the retirement stock are the **absence of substitute technologies**, **low knowledge about the performance of technologies at scale, low knowledge about the harms of the current technology,** and **the presence of entrenched incumbent technologies.** Unlike the discussion of the STCs that affect innovation mechanisms and processes at other stages, we discuss the STCs of several stages at once in this section as they relate to obsolescence mechanisms. In the absence of competing substitute technologies, demand for a *technology in limited or widespread use* is likely to be strong, so the retirement mechanism of decreased demand will be weak even if the technology is considered to be problematic. Similarly, if there is low knowledge available about performance of *feasible technologies* if they were to be expanded in scale, harms only revealed at scale are unlikely to provide sufficient incentive to retire technologies. Further, if little information is available about the harms of *feasible technologies*, currently available risk assessments are unlikely to provide sufficient information to drive obsolescence processes. Finally, the presence of entrenched incumbent technologies that are already "locked in" in a socio-technical system can weaken the ability of decreased demand or disadvantageous relative cost to drive retirement of *technologies in limited or widespread use*. Finally, actors who benefit from incumbent technologies often slow retirement processes, even when new technologies are available that provide greater benefits to sustainable development. Power and politics**,** when retirement of incumbent technologies creates winners and losers, can often create inhibiting conditions.

None of our cases focused on a technology that was being retired, but in many of them one of the main challenges that proponents of the technology found was to displace the existing incumbent Ceramic water filters and cookstoves had to compete with traditional practices for sourcing water and heat, cassava bread had to compete with the white bread, the existing malaria drugs had to compete with the existing drugs, and drip irrigation had to compete with traditional practices of flood irrigation which required little to no investment on the part of adopters unlike relatively high up-front investments required for drip.

There is also the opposite problem, when technologies are prematurely discarded. Fashion, or "sexiness" of alternatives, may lead to certain incumbent technologies entering into the obsolete technology stock while they still have potential benefits for some users. This is closely related to the selection mechanisms, in the sense that the selection and eventual dissemination of a "sexy" technology may displace existing technologies, regardless of the relative benefits of the incumbent. Premature retirement may also occur if the market returns are inadequate to incentivize ongoing supply, as has happened from time to time for medicines for which the market is small or uncertain.

4.7 Summary of STCs Inhibiting Flows

We believe that the model of the innovation system that emerges from this work is comprehensive and inclusive of other attempts to conceptualize innovation in the existing literature in a variety of sectors.[39] Our conceptual model also ties disparate literatures together; in particular we draw the link between the literature that focuses primarily on the invention and production stages of innovation and literature that focuses more heavily on adoption and sustained use. This model also goes beyond existing literature. Our focus on the factors that make it difficult to change from one sociotechnical configuration (which involves not only technological changes, but also changes in user practices, regulation, industrial networks, etc.) to another was particularly influenced by the literature on technological transitions.[40]

In summary, along various pathways of the innovation system, technologies with certain STCs are more likely to be unable to deliver benefits to end-users without some type of intervention. In the following section we examine what role transnational actors and institutions can play to ease these impediments.

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[39] For example: Chain-linked model in: Kline, S.J., and Rosenberg, N. (1986). An Overview of Innovation. In: Landau, R., and Rosenberg, N. (Eds). The Positive Sum Strategy: Harnessing Technology for Economic Growth, 290. Gallagher et al. develop a model of innovation in the context of the energy sector using different terminology in Gallagher, K.S., Grubler, A., Kuhl, L., Nemet, G., Wilson, C. (2012). The Energy Technology Innovation System. Annual Review of Environment and Resources 37: 6.1–6.26.

[40] Geels, F.W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case study. Research Policy 31: 1257–1274. [And:] Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., and Smits, R.E.H.M. (2007). Functions of innovation systems: A new approach for analysing technological change. Technological Forecasting and Social Change 74 (4): 413–432.

Part 5. The Transnational Functions of Actors and Institutions

5.1 Typology of Transnational Functions

Our case analysis highlighted a number of ways in which transnational actors or institutions overcame STCs that inhibit the flow of different types of technologies through the innovation system. Building on these insights, alongside the combined work of scholars of public policy and political science,[41] we found that increasing the benefits of technological innovation for sustainable development can, in some cases, imply a need for transnational engagement of actors or institutions when at least one of two conditions apply:

1. Transnational collaboration can achieve objectives more effectively or efficiently than national action alone (e.g., in the presence of cross-border externalities, economies of scale); or
2. National innovation systems have a shortfall of necessary resources (e.g., information, expertise, skills, financing, normative authority, or convening power).

From the cases, we inductively identified **eight** transnational functions that actors and institutions can and sometimes do perform in the global innovation system:

1) setting goals, priorities and agendas;
2) reducing transaction costs (e.g., through rules and standards);
3) reducing information asymmetries;
4) internalizing (trans-national) externalities
5) reducing social distance;
6) building capacity;
7) reducing costs, and
8) reducing risk.

Some of these functions may benefit all countries, regardless of their level of development, while others may be particularly useful to countries with less developed national innovation systems. For example, in agriculture, countries with strong agricultural extension services may only require information provision to extension agencies, whereas in locales with weaker or non-existent extension programs, transnational actors may be essential for building capacity at local and individual levels. Similarly, in a globalized medicines market, wealthier countries may benefit from reduced transaction costs linked to the establishment of international quality standards, whereas poorer countries may require a reduction in the (net) costs of a medicine in order to make it accessible. Furthermore, some of these functions are closely interrelated. For example, reducing

[41] Hood, C. (2007). The Tools of Government in the Digital Age. New ed. Public Policy and Politics. Basingstoke: Palgrave Macmillan. [And:] Howlett, M. (2011). Designing Public Policies: Principles and Instruments. New York: Routledge Textbooks in Policy Studies. [And:] Frenk, J. and Moon, S. (2013). Governance Challenges in Global Health. New England Journal of Medicine 368: 10. [And:] Ruggie and Clark – unpublished slides.

transaction costs will also reduce (net) costs, reducing information asymmetries may reduce risk, and reducing risk will often reduce (net) costs. Nevertheless, we found it analytically and conceptually useful to separate out these functions, as explained further below.

Not every transnational function will always be appropriate. Rather, the STCs and context surrounding a technology at a given point in time provides useful guidance for when a certain function should be considered (Table 4).

Table 4. Transnational functions in response to inhibiting conditions for different flows

Conditions that inhibit flows (condensed from Table 3)	**Potential Transnational Function**	**Example of intervention**
1. Flow from the Knowledge stock to the Invention Stock (**invention flow**)		
a) High risk-adjusted cost of invention	-Reduce costs -Reduce risks	-International public or philanthropic funds to subsidize invention costs -Procurement guarantees from international actor for final invention
b) Highly mundane technology	-Set goals, priorities, agendas -Reduce costs	-Channel international public R&D investments to "mundane" but beneficial technologies
2. Flow from the Invention stock to the Feasible Technology Stock (**selection flow**)		
a) Selection by agents with high social distance to principals	-Reduce social distance -Reduce information asymmetries -Build capacity in selectors, or principals (to reduce reliance on agents)	-Build networks, i.e., through international workshops -Transnational performance testing of new technologies -Policies for systematic evaluation of technology dissemination projects, and publication of results
b) Selection by laws, policies or regulations inapt for sustainable development	-Reduce information asymmetries	-Transnational funding of comparative national research to adapt laws, policies or regulations
c) Highly mundane technology	-Set goals, priorities, agendas	-Transnational funding of objective assessments of potential impact of technologies
d) Low potential return on investment	-Reduce costs or risk	- Transnational purchase guarantee to reduce risks and increase returns to producers

e) Low level of modularity	-Reduce transaction costs	-Guidelines for modularity in technology components -Financial incentives to develop modular technologies
3. Flow from Feasible Technology Stock to Technologies in Limited Production/Use (**production and early adoption flows**)		
a) High relative prices (linked to costs of production or adoption) to users	-Reduce costs -Reduce risk	- Transnational provision of low-interest loans -Transnational purchase guarantees to jump start markets to reach economies of scale -Transnational provision of time-limited subsidies to early-adopters
b) Small size of organization manufacturing or adopting	-Reduce transaction costs -Reduce information asymmetries -Build capacity	-Transnational provision of information -Transnational training for capacity building
b) High infrastructure needs (physical or human)	-Build capacity	-Transnational provision of advice, training or expertise
c) Intellectual property protection used to extract monopoly rents	-Build capacity	- Implement limited exceptions to patent rights
d) Absence of standards or guidelines for production or adoption	-Reduce transaction costs -Reduce information asymmetries	-Develop international guidelines -Transnational financing of research required to develop guidelines
4. Flows from Technologies in Limited Production/Use Stock to Technologies in Widespread Production/Use Stock (**production and widespread use flows**)		
a) High relative prices (linked to costs of production, adoption or IP/patents) to users	-Reduce costs -Reduce risks	-Transnational subsidies -Implement limited exceptions to patent rights
b) High infrastructure needs (human and physical)	-Build capacity -Reduce costs	-Transnational training programs to build human infrastructure -Transnational loans for physical infrastructure
c) Absence of standards and guidelines for use	-Reduce transaction costs -Reduce information asymmetries	- -Develop international guidelines -Transnational financing of research required to develop guidelines

d) High social distance between original and new users	-Reduce social distance	-Convening
e) Revealed disadvantages	-Reduce information asymmetries	-Support earlier-stage research on disadvantages
f) High network externalities	-Internalize externalities -Reduce costs	-Transnational temporary subsidies to encourage early adoption and build network effects
5. Widespread Production/Use Stock (**adaptation flows**)		
a) High social distance between original users and new users	-Reduce social distance	-International support for dialogues with end-users to elicit the social, cultural and technical requirements of a technology in different contexts
b) Low capacity of end users to adapt technology	-Build capacity	-Transnational training programs such as agricultural extension services
c) Low level of modularity	-Reduce transaction costs	-Guidelines for modularity in technology components -Financial incentives to develop modular technologies
6. Flow into the Obsolete and Retired Technology Stock (**retirement flow**)		
a) No substitute technologies available	-Set goals, priorities, agendas	-International agenda-setting and/or financing to stimulate invention of substitutes
b) Low knowledge about alternative technologies at scale or risk assessment	-Reduce information asymmetries	-International funding of research and field-testing of alternate technologies at scale
c) Entrenched incumbent technology	-Reduce costs	-International subsidies on alternate technologies

As reflected in Table 4, a transnational function may only be useful for some technologies or at some points in the innovation system, and will vary greatly by context.

For example, we found that for technologies with high risk-adjusted of invention, governments, corporations, and non-profit organizations could play significant transnational roles in enabling invention. Invention in the heat-stable vaccine, carbon capture and storage, and cocoa genome cases are all high-risk and high-cost. While there is a large latent demand for heat-stable vaccines, financing has been difficult to secure and heat-stable technologies have been slow to emerge in part because of the high risks and costs involved. A promising heat-stable technology was able to advance in development due to the contribution of intellectual property by academic researchers, student social entrepreneurs who secured small amounts of seed funding, and in-kind contributions by a non-profit technology development organization in the early stages of the technology; only after some risk was reduced as the technology advanced was it possible to secure an initial philanthropic grant, followed by interest from large pharmaceutical firms and venture capitalists. In the Carbon Capture and Storage case, governments around the world have been supporting technology development with investments in the hundreds of millions of dollars, and several international organizations have tried to pool information to inform future efforts. In the case of the Cocoa Genome Project, its speed and success were made possible by investment from the private sector (around $10 million by the Mars Corporation) and built on existing research priorities of the United States Department of Agriculture.

Some of the cases covered technologies with relatively low invention costs and were categorized as "mundane," but still entailed some degree of risk. In these cases, the transnational actors were smaller entities, such as researchers at academic centers in high-income countries or smaller NGOs. For example, invention of cookstoves for use in Darfur, Sudan was accomplished due to the drive of researchers at UC Berkeley and other academic centers, who served as champions for the cause. They managed to garner significant in-kind research support to make up for the scarcity of grant funding available to meet invention needs in areas that do not overlap with the invention needs of high-income countries. This was only feasible because the invention costs were relatively low. Similarly, ceramic pot filters became popularized as a result of the effort and drive of committed individuals and organizations, such as the NGO Potters for Peace. The cassava bread technology in Nigeria was the result of investments into research at the International Institute for Tropical Agriculture (IITA). Here, the host country of an international organization reaped the benefits of having researchers on their doorstep with whom they could collaborate on technology inventions to meet domestic needs. These cases highlight that there is interest and capacity to invent low-cost technologies for use by poor populations, but that these efforts may happen in an *ad hoc* manner that could benefit from more concerted, targeted or well-financed approaches.

The cases also highlighted problems with selection of technologies poorly-suited for end-user needs. To counteract the problem of high social distance between selecting agents and end-user principals, transnational actors could change power dynamics by building the networks and expectations of end-user involvement in selection processes, and/or building the capacity of end-users to select technologies for themselves. In situations in which selection will continue to be done by agents that are not end-users, transnational actors could improve the quality and quantity of information available to the selecting agents on technological performance by, for example, conducting testing and providing performance comparisons of a variety of available technologies. For cases where existing national laws or policies create barriers to the selection of a beneficial technology, transnational actors could support research and sharing of evidence that could inform the amendment of national/local legal and regulatory frameworks. When such laws or policies exist at the transnational level, such as trade or environmental agreements, transnational action will be necessary to make any amendments.

Transnational intervention may also play an important role in expanding access to technologies with high costs to end-users, as was illustrated in the case of Affordable Medicines Facility-malaria, in which a global donor-financed subsidy was implemented on newer-generation antimalarials to facilitate uptake especially in rural areas. However, the concept of "cost" includes not only the price the technology itself but also the supportive infrastructure required to deploy it over the long-term, as well as considerations of environmental, health, and social impacts. These broader costs were illustrated well in the water filter case, in which filter production alone was not enough, but rather much larger investments for distribution and maintenance were required than originally thought, and getting people to adopt and use the filters required many hours of field work. Thus the role of transnational actors may extend beyond subsidizing unaffordable prices, to also investing in the human or physical infrastructure needed through training, maintenance, education, monitoring and evaluation.

There is also an important role for transnational actors or institutions in information provision. The cases illustrated that when the actor adopting a technology was small, the costs of getting access to strategic information could discourage uptake. For example, for drip irrigation and the System of Rice Intensification, merely making the technology available to small-holder farmers was not adequate to convince them to adopt these innovations. Rather, further interventions were needed to reduce information costs and risks for smaller-scale end-users. This is especially true when the sustainable development goals of the technology do not directly overlap or align with end-users goals for the technology, and adoption depends on users acquiring new understandings and assimilating new or different values. For example, with cookstoves, transnational actors could provide information to users on the link between smoke and illness, increasing the likelihood that users would select a stove that reduces smoke.

A full discussion of all the potential types of transnational interventions would require far more space than available here. But we list some possibilities for consideration in the third column of Table 4, some of which have already been implemented for some technologies and others of which remain ideas for consideration.

Having now established the transnational functions and points at which they may be required in the system, the question arises as to which actors or institutions should perform these functions. To help identify these actors or institutions, we identified five types of resources required to perform each of the functions listed (see Table 5):

Table 5: Resources required by actors & institutions to perform transnational functions

Resource needed to perform function	Transnational Functions
a) Normative authority	Set goals, priorities & agendas Reduce transaction costs Internalize externalities
b) Convening power	Reduce transaction costs Reduce social distance Build capacity Internalize externalities
c) Information	Reduce transaction costs Reduce information asymmetries Reduce social distance Reduce risks
d) Expertise/skills	Build capacity
e) Finance	Internalize externalities Reduce (net) costs Reduce risks Build capacity

The resources required to carry out a function underscore the conclusion that different types of actors or institutions will be more appropriate than others to perform a particular role. For example, some actors may have finance or skills, but not the normative authority to set public goals, priorities or agendas. Rather, contemporary governance norms demand that such a function be performed by an actor with some kind of democratic legitimacy, such as a government or intergovernmental body such as the UN General Assembly or global processes such as debates over the post-2015 Sustainable Development Goals. Similarly, certain types of actors may be particularly well-placed to build capacity, such as an international NGO or research institute with technical expertise. At other times, such as for capital-intensive projects, large-scale financial resources will be needed that can only be mobilized from a few actors, such as large foundations, firms or governmental bodies. These brief illustrations highlight our conclusion that a strengthened global innovation system does not necessarily imply the construction of a global, centrally coordinated innovation system. What we have tried to propose is a framework to better understand when, and how, actors can perform transnational functions in ways that help realize the larger potential benefits of different technologies that are considered to have potential to support sustainable development.

5.2 Utility of the Transnational Function Framework

Many of the functions and interventions listed in Table 4 are already performed in some countries at the national level and, for some technologies, at the transnational level. For example, the World Bank has long provided low-cost loans to build certain kinds of infrastructure and the International Finance Corporation has long provided low-cost financing to private enterprises to subsidize or reduce risk. The World Health Organization routinely develops international guidelines for the treatment of certain diseases, or quality assurance for the manufacture of certain medicines. The CGIAR has long subsidized invention costs for agricultural technologies, and the US National Institutes for Health has long run international training programs for health researchers in developing countries. International aid agencies and NGOs regularly subsidize the costs of certain technologies, such as cookstoves, water filters, and RUTF for populations undergoing emergencies or living in chronic poverty. These examples demonstrate important precedents for carrying out certain transnational interventions.

However, institutional arrangements at the transnational level tend to be weaker and more sparse than in well-developed national innovation systems. That is, not all functions are necessarily performed for all relevant technologies, nor across the full breadth of the innovation system from invention to retirement. For example, budgetary and organizational capacity constraints mean that the WHO quality-assurance program only covers health technologies for certain conditions (e.g., HIV/AIDS, tuberculosis, malaria, contraception, and vaccines), but excludes the many other medicines needed for a functioning national health system. For other types of technologies, such as ceramic water filters, international quality guidelines do not exist nor is there an entity mandated to carry out quality assurance. Donors subsidize R&D for the invention of new drugs for neglected diseases, but are not necessarily willing or able to support the training of health workers required down the line to use such new technologies safely and effectively. Solar panels that do not meet quality standards were deployed for many years in Kenya because of a lack of quality testing facilities in the country. These examples highlight where the greatest utility of this framework may lie: as a diagnostic roadmap for where gaps may arise in the innovation process (by sociotechnical condition) and a set of transnational interventions that may be useful for bridging them.

To illustrate: for technologies characterized by the STC of high risk-adjusted invention costs, there may be a strong case for internationally-pooled funds to reduce R&D costs and risks. Such funds could be channeled through a new organization such as the Green Climate Fund, or through existing ones such as the World Bank. For technologies where the end-user is a small organization or entity, such as a farming household, facilitating the uptake of technologies may require international support for training and information provision, for example through extension services. Support for such services could be provided by governmental bodies, philanthropic actors, NGOs, or research institutes, among others. And where there are high relative prices to end-users for highly beneficial technologies, there may be a strong case for international subsidization in the short- or longer-run. Transnational efforts should also include mechanisms to collect information from end-users and feed it back into the system, particularly when there is a high social distance between inventors or selectors and end users, such as cataloguing different local inventions or adaptations to existing inventions, or improving understanding of local needs. Transnational conveners could be especially valuable in bringing together more localized efforts or actors.

Part 6. Conclusions

The growing number of actors and institutions that wield transnational influence on innovation processes means that attention to national innovation systems alone is no longer sufficient to fully understand innovation processes. This is very much in line with scholarship that has expanded thinking around governance beyond the nation-state, across a broader range of actors and scales. While the contours of a global level innovation system are beginning to emerge, demanding attention and careful stewardship, the community of scholars and practitioners do not yet have a common language or conceptualization of the whole system to inform a comparative analysis across different technologies and sectors.

At the same time, as debate over the future of the post-2015 Sustainable Development Goals intensifies, it is clear that existing innovation systems (including but not limited to the global dimension) is not likely to be adequate to meet them. While there have been considerable achievements within specific sectors or at the national level, the global innovation system as a whole remains fragmented and inchoate.[42] Despite *ad hoc* activity by different actors to fill gaps in the global innovation system, significant opportunities are not being seized for transnational interventions to broaden the potential benefits and minimize the potential harms of technological innovation. More systematic approaches to analyze and strengthen the trans-national level for specific cases are still needed to achieve meaningful sustainable development gains.

This project has sought to contribute to these goals by offering a conceptualization of the global innovation system that works across various sectors and types of technology—a framework to diagnose which transnational functions may be required and when. This framework, which we developed inductively based on 18 case studies across five sectors and a literature review, describes the movement of technologies through six stocks (Knowledge, Invention, Feasible technology, Technologies in limited production & use, Technologies in widespread production & use, and Obsolete and retired capital) along seven types of flows: Invention, Selection, Production, Initial Adoption, Widespread Use, Adaptation, and Retirement. We then identified the sociotechnical conditions and mechanisms that frequently impede the flow and evolution of technologies from one stock to another.

Our analysis indicates that inhibiting and enabling conditions may be more similar across sectors than within them, given the heterogeneity of technologies within a sector. This observation underscores the importance of looking both within and across sectors, and developing common languages and frameworks to facilitate cross-sectoral collaboration and learning.

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[42] Juma, C., Lee Yee-Cheong, and UN Millennium Project. (2005). Task Force on Science Technology and Innovation. Innovation : Applying Knowledge in Development. London: Earthscan. [And:] InterAcademy Council. (2004). Inventing a better future: A strategy for building worldwide capacities in science and technology. Amsterdam: InterAcademy Council. Retrieved from http://www.kva.se/Documents/Vetenskap_samhallet/Inventing%20a%20Better%20Future.pdf.

While the frameworks we have developed are applicable to all areas of technology, our case analysis focused on technologies that may foster sustainable development, where considerations of intra- and inter-generational equity carry particular weight. Expanding the benefits of technological innovation for sustainable development will require the global community of transnational actors to strengthen its capacity to carry out eight functions to improve the effectiveness and efficiency of the overall system, and to bridge gaps in national innovation systems. In practice, the timing of when each function is relevant, and the choice of application is highly context- and technology-specific, but we have identified certain sociotechnical conditions that suggest where particular attention should be paid.

Finally, our analysis concluded with a broad set of transnational interventions that should be considered, ranging from international financing of invention, to network building to reduce social distance to end-users, to training programs to build capacity to adapt technologies on the ground; from convening to set agendas and priorities, to research to inform guidelines for use. Our conclusions do not provide a blueprint for how to build a monolithic global innovation system—that is far from our intention. Rather, building on efforts and experiences of the past decade, we offer frameworks for analyzing where weaknesses are likely to arise in the innovation process, identifying when certain transnational functions should be considered to increase the contribution of technological innovation to meet human needs. We hope the application of these frameworks will contribute to achieving ambitious sustainability targets agreed in the global arena, and increase the potential contributions of technological innovation for sustainable development. And we hope that future scholarship will improve these frameworks based on new cases, analysis and experience.