Human Capacity Issues Along the STEM Pipeline*

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ABSTRACT

The development and maintenance of human capacity in economies is critical to long term competitiveness, but also for the overall health and environment of regions. Yet, human science and technology-based capacity is multidimensional and has interrelated characteristics which present certain policy challenges. This paper addresses a range of issues specific to a discussion on human capacity in S&T. First, the paper emphasizes the importance of acknowledging the complexity of human capacity issues and how they evolve along the STEM (science, technology, engineering, and mathematics) pipeline. The pipeline is an often used reference to describe the training and development in STEM disciplines, from early childhood education, to more advanced training, and finally to professional collaboration and interaction and serves as a useful organizing framework for the discussion of capacity along the career evolution process. Second, the paper offers an organizing framework for discussion of policy mechanisms that have been developed to address issues and gaps that occur along this STEM pipeline. Specifically, it contrasts the traditional mechanisms of building human capacity in STEM areas with newer "gap filling" and integrated approached to addressed human capacity disparities and priorities. Third, the paper addresses core challenges in human capacity in STEM, including the education and training, participation of women and underrepresented groups, brain drain/brain circulation issues, and the globalization of science. The paper concludes with a discussion of policy implication for the development of human capacity.

KEYWORDS: human capacity, STEM careers, women in science, brain drain, globalization

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1. INTRODUCTION

A productive, competitive system of science, technology and innovation (STI) depends upon certain science and technology related capacity. Scholars generally support the view that to be effective, science and research policy should center not only on scientific outcomes, but on the growth and continued development of capacity (Bozeman, Dietz and Gaughan, 2001). Indeed, issues of capacity development are increasingly discussed in science policy communities as a critical policy area in which to focus.

Yet, capacity is multidimensional and has interrelated characteristics. For example, the ability to conduct scientific research is dependent on infrastructure capacity, including laboratory facilities, research and computing equipment, and increasingly, a robust cyberinfrastructure system. Institutional/policy capacity is also core to the development of a competitive STI system. Research funding, research priorities and the ability to transfer funds within and across systems supports scientific work. A jurisdiction's economic capacity is also necessary to provide the demand for a scientific workforce, and provide an attractive environment in which to work.

Yet, even the most sophisticated infrastructure or creative policy institutional environment cannot supplant the core of any innovation system – science and technology human resources, or human capacity. The human element is the backbone of the scientific enterprise, the creator of new knowledge and the conductor of scientific research. Further, it is inextricably entwined in the other aspects of capacity as they relates to the development of a competitive, sustainable, and impactful STI system.

The purpose of this paper is to review the multiple dimensions and challenges of human capacity development as they relate to an effective, competitive STI system. Ideally, it should stimulate discussion and debate around appropriate and effective policy mechanisms regarding human capacity. In this paper, the challenges to capacity development in science are addressed. To organize this discussion, a framework for conceptualizing capacity-related policy approaches is presented, followed by a discussion along the timeframe and sequence of the STEM pipeline. The paper concludes with a discussion on key issues in implementing and evaluating human capacity policies in the STI environment.

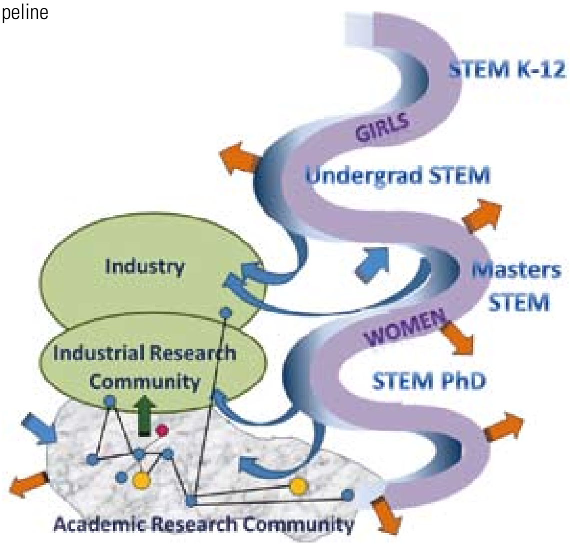
2. THE STEM PIPELINE

In considering the complexities of capacity in the STI context, the growth of capacity is generated from the accumulation of "scientific and technical human capital" (S&T human capital), which includes both human capital endowments such as formal education and training, and social relations and network ties (Bozeman, Dietz and Gaughan, 2001; Bozeman and Corley, 2004). In effectively addressing human STI capacity, an important challenge is presented in that capacity issues arise very early in scientific careers, feeding into an educational "pipeline" of education and workforce development (Figure 1). This pipeline refers to the career development stages, from early educational foundations, to high school and college education, choosing science as a career, production of STEM (science, technology, engineering, and mathematics) doctorates, and to maintaining interest and developing skills in science and technology. It is frequently used as a framework for discussing the development stages of a science and engineering career.

The pipeline is a useful organizing framework for the discussion of capacity because of the consistent opportunities and challenges for building capacity at various career stages. Any comprehensive discussion of human capacity in research should acknowledge the intertwined capacity issues and challenges that are presented along this pipeline. For example, (Figure 1) the STEM pipeline is not uni-dimensional, but incorporates issues along education and career stages, and also incorporates different groups, where women and underrepresented minorities may have different experiences challenges, and outcomes. Overall, it may be more accurately described as dynamic, where there are changes in participation in the STEM workforce, including issues of exit from science overall, or from economies through "brain drain" and re-entry at various career stages. The pipeline feeds a range of career possibilities, including those in applied industry and education careers (particularly by undergraduate and master's degreed individuals) and to academic and industry research careers for doctoral recipients.

Within these careers, there are also certain dynamics and characteristics relevant to a discussion of human capacity. For example, science is increasingly collaborative and involves networks of collaborators and colleagues that may cross disciplines (represented by different colors), sectors (represented as different areas) and distances (represented by longer and shorter connecting lines). The ability to create and benefit from these ties is an important aspect of scientific human capacity (Bozeman and Corley, 2004) where resources are exchanged across intuitions, sectors, and economies. In some cases, this may also involve the movement of researchers between academic and industrial research organizations. Finally, there are opportunities for re-entry to scientific and technology careers (represented by inward pointing arrows), either later in the educational process, or as a later career change. Together, these characteristics of the pipeline and its environment underscore the complexities of addressing human capacity issues. In order to meaningfully address human capacity issues in STI, these characteristics should be acknowledged and addressed in policy mechanisms and initiatives.

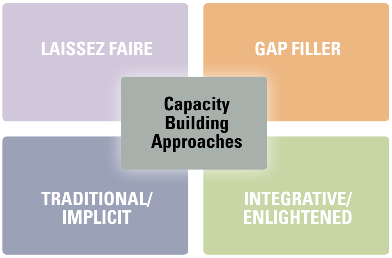
FIGURE 1 STEM Pipeline



3. POLICY CONTEXT FOR ADDRESSING CAPACITY

Given the intertwining complexity of issues and related challenges to the development of effective human capacity in STI, how has it been approached in STI policy/initiatives and what new responses are emerging? How might current policy approaches be categorized? To which specific issues are policy initiatives responding? Which approaches seem the best conceptualized to truly impact capacity development? Efforts to advance human capacity in STI may be generally grouped in four categories (Figure 2.). On the left hand side, policies where the development of human capacity is implicit represent long-standing approaches to capacity development, whereas the right hand side of the figure shows more deliberate attention to human capacity in science.

FIGURE 2 General Classification of STI Human Capacity Policy Approaches



To begin, the combination of existing mechanisms for funding both public and private R&D have implicit embedded human capacity development expectations. While these are not truly "human capacity" policies per se, they are important to mention because they reflect the long standing approach to the building of human capacity in STI through normal research support and funding processes. For example, particularly for applied research and technology, economies rely heavily on industry to support research, technology transfer, and other related programs. All economies to some extent assume a "laissez-faire" approach where the market drives the direction, prioritization, and attention to particular research areas and is funded by industry. Human capacity then develops across society and the scientific community through technological advance, market technology demands, and market workforce demands. It is generally not an explicit objective of these processes, but is an assumed outcome.

Related, S&T policy has often approached the development of human capacity as a natural outcome of the support of scientific research or basic education funding for some time. Therefore, traditional approaches to human capacity development may be described as those approaches that focus on enhancing the quality and outcomes of the educational system overall, or basic and applied research funding support where human capacity issues are not explicit.

From an early pipeline perspective, for example, it has been considered reasonable to assume, that funding improves schools, educational processes and learning across all fields will also improve. Later in the pipeline, a parallel expectation has been evident through traditional support and funding mechanisms where the expectation is that if programs are funded to conduct research, technology transfer, and other related programs, that the personnel involved in these projects and programs will also benefit. Human capacity outcomes have generally been demonstrated through the numbers and demographic composition of personnel. For example, standard funding agency reporting requirements may include number of students, faculty, other researchers supported in the project. Data may also be broken out by rank, gender, and ethnicity to capture participation of underrepresented groups.

Overall, the reliance on human capacity development as a normal and expected outcome of supporting science and technology in general is not ineffective, but evidence suggests that certain groups in particular are disadvantaged without some deliberate attention. For example, performance in STEM fields in the K-12 years is highly variable across and within economies around the world, women and underrepresented groups remain poorly represented and are difficult to attract and retain in many areas of science and engineering (NSF, 2007) and researchers experience significant barriers in collaborating across distance (Cummings and Keisler, 2005). Among other evidence, these examples demonstrate that there remain many areas where significant improvements may be made along various stages of the STEM pipeline. Certainly, sufficient levels of research funding have a range of impacts that address human capacity in research. Yet, much of the dialogue around the need for human capacity in STI is based on the gaps that may not be filled through traditional approaches to effectively build and maintain human capacity in STEM fields and careers. To state the obvious, if this non deliberate approach were fully functional, we would have little to no concerns about the state of human capacity issues in regard to science, technology and innovation. Given that those concerns exist, suggests that these mechanisms are inadequate for accomplishing these goals. In response the evolution of attention to human capacity in STI has led to the development of two additional broad categories of policies that complement, and in some cases supplement, larger traditional approached to the support of science and STEM related programs: "gap filler" policies, and those of a more "integrative" nature.

To guide the discussion, a framework for these general categorizations of policy approaches is summarized in Table 1. Gap filler policies have generally emerged in response to recognized inequalities in a given economy that deserve some deliberate attention, such as issues of attraction and retention of women and underrepresented minorities to STEM careers. Yet, gaps may also exist across an economy in different ways. For example, in all economies, regional variations exist in research capacity, reflecting concentrations in clusters of jurisdictions, or types of research institutions, laboratories, and other institutional resources. Relative disadvantages then may be addressed through deliberate programming and funneling of resources.

The ways in which the origin and explanation for these "gaps" are interpreted then guide the development of the policy approach. For example, in the area of women in science, explanations for why underrepresentation is so prevalent ranges from work-family balance issues, to inadequate mentoring and role models, to early childhood education approaches that do not encourage girl's participation in science. Some policy and programmatic approaches blend interventions and initiatives that address a bundle of issues, others may be more targeted and address only one aspect. It is beyond the scope of the paper to review the myriad explanations for gaps in STEM-related capacity. Overall, however, it should be recognized that the range of policy mechanisms to identify capacity gaps or inequities are designed to address the sources and symptoms of these gaps.

4. ISSUES AND POLICY INITIATIVES ALONG THE STEM PIPELINE

Given this framework, what are the critical issues in human capacity development in STI along the pipeline, and what are some examples of policy responses to address these issues? This section highlights some of the critical issues and policy discussions around human capacity. It first addresses

TABLE 1 Classification of Human Capacity Policy Mechanisms: Example from the U.S.

Human Capacity Policy	Human Capacity Focus	Mechanism for Enhancing STI Human Capacity	Example	Sample Outcomes/Evidence of Human Capacity Effects
Laissez-Faire	Implicit	Funding of research involves participation of industry researchers.	General industry funding of research.	Quality of research outcomes, participation in research.
Traditional	Implicit	Funding of research, particularly large research projects, involves participation of researchers and students.	General public funding of scientific research, general education funding	Quality of research outcomes, participation in research.
Gap Filler (Social)	Explicit	Targeted research grants programs for specific underrepresented populations or other, career development enhancement for these groups, funding educational program for young scientists and youth	US NSF ADVANCE, US NSF REU, US NSF Young Career Grants	Increased retention of women in science, increased STEM majors, increased research productivity of young scientists.
Gap Filler (Regional)	Explicit	Targeted programs for specific geographic areas intended to provide set-aside funds for less competitive areas.	US NSF EPSCoR US NIH INBRE programming	Increased federal R&D funding, increased participation of under-represented populations in research, regional participation and impacts of research, regional research networks
Integrative	Explicit	FEmbedding/requiring certain human capacity/resource aspects and/or outcomes as part of research funding mechanisms; coordinating educational policy with STI capacity objectives.	2007 American Competes Act, incorporation of human resource in research support and experiences.	Increased collaborative interaction, interdisciplinary knowledge exchange, research impacts, diverse S&T workforce.

education, training and development of the STI workforce. Here, attention to issues specific to the educational system are presented along with content issues related to the ability to meet the needs of industry. Next, the discussion addresses the dynamic and representational aspects of the pipeline in regard to human capacity. This is followed by a discussion of the systemic issues specific to human capacity. Issues of brain drain and regional characteristics of human capacity within and across economies is addressed here as a way of addressing capacity on a macro scale. This section is then followed by a concluding section and discussion of the need for effective and meaningful evaluation in order to enhance the evidence-based policy making in regard to human capacity issues. The purpose is not to treat any of these issues in depth, as there are extensive literatures on each. Instead, this paper briefly reviews each and then presents examples of policy responses to address the specific challenges. Because traditional and laissez-faire approaches often do not directly and explicitly address human capacity, *the focus of this paper is on gap filler and integrative approaches due to the deliberate nature of these policies in addressing human capacity development.*

Education, Training, and the Development of an STI Workforce

First, early in the pipeline, the ability to increasingly attract students to STEM fields has been identified as a global "crisis" where some countries have experienced significant declines, and others only minimal gains, in entry to scientific disciplines (OECD, 2008). A recent global study of student interest in S&T disciplines, for example, found that half of the seventeen countries examined had experienced a percentage decline in student interest in S&T fields (OECD, 2008.) Yet, the development and capacity of a scientific workforce depends heavily on a strong early educational foundation that prepares students in science and technology, and builds and maintains interest in scientific careers. Thus, the "pipeline" that feeds the scientific enterprise begins in the early educational years, where issues of capacity in science begin at a very early developmental stage.

What challenges to capacity development are particularly pervasive at this early education stage? Through policy discussion and scholarly studies, the ability to attract students to STEM disciplines has been recognized as particularly complex. In this regard, several challenges exist that present issues for successful policy responses. Categorically, issues abound in the areas of student interest and preparation, educational approaches and resulting learning. There is currently considerable attention being paid to enhancing the quality and attractiveness of early elementary education in STEM fields. For example, today's youth may be more comfortable and familiar with technology at a much earlier age, which may impact learning and interest.

Second, moving along the pipeline to the high school and even undergraduate education years, while the attraction of students is an important challenge, the difficulty of retention also emerges. Once students enter scientific disciplines, significant challenges remain in retaining their interest and involvement in these disciplines. Distinct, yet related, challenges exist at various stages of the educational pipeline – from elementary education through the college years. The pipeline has been referred to as "leaky" where interests and/or participation in science wane, particularly for women and minorities. While the core issues related to capacity early in the STEM pipeline are based on a sound educational foundation, other societal issues are also apparent. For example, the ability to attract and retain students in the sciences has also been linked to public support for science and the recognition of scientific careers as viable and attractive. Thus, studies have also addressed public understanding of science, scientific research, and the role of science in society. For example, research have demonstrated significant barriers to the selection of STEM disciplines for girls based on societal or family expectations (Chinn, 2002), where parental influence on student entry to STEM is particularly problematic for females. Clearly, contemporary views and expectations for careers influence the attractiveness of scientific and engineering career paths. Following the pipeline further, retention issues remain relevant throughout the early career stages, where trends in professionals leaving scientific careers have been observed (Preston, 2004.)

The resulting responsibility on the educational system to address these issues and to provide the appropriate foundation and training is significant. This is a critical issue because the development and sustainability of human capacity in the STI environment is dependent on the attraction, training, and retention of a scientific and technical workforce. Simply put, if students do not develop an adequate foundation and early interest in STEM (science, technology, engineering, and math) concepts and content, they may not have the capacity, nor the interest to continue in their development. Recognizing geographic variation in these issues is also relevant. For example, significant differences may exist in particular interests in science between students from developed and less developed economies. Further, the quality of STEM education in less affluent schools and regions inhibits the development of interest in STEM and entry to STEM disciplines. In some areas, in regard to schools themselves, there are facilities issues in terms of technology and materials in the classroom, as well as other classroom issues. Specific to human capacity, teacher training and awareness of newer learning research is also relevant. Understanding of learning processes has advanced among educational scholars, thereby suggesting new and innovative approaches to science and technology learning. Teacher training may not then develop adequate capacity to train the emerging STEM workforce. Related, with increasing interdisciplinary expectations of scientists, this also addresses the importance of student learning across disciplines in order to have the capacity to function in that environment.

From college through the professional years in the STEM pipeline, a related and **third** critical issue emerges in educating scientists and engineers. It is the ability to effectively train and prepare researchers and other technical staff to be competitive, attractive and productive in the industrial-applied workplace. The capacity of educational systems to effectively funnel scientists and engineers for work in industry depends on an appropriate education system that includes marketable content learning, but also may be positively influenced by strong university-industry ties within an economy. This requires the development of skills that adequately meet the market demand for specific skills and knowledge. Relevant to human capacity in particular, is the training and socialization that can enhance the industrial technical workforce, but also build academic-university-industry cross sectoral linkages. Technology and knowledge transfer from the academic research environment to industry is critical to the sustainability and growth of economies. However, this transfer ranges from traditional views of the transfer of technology, to the development, training, and subsequent transfer of human resources. The human resource exchange occurs through collaborative interaction, the training of employees for industry employment, and the sharing and swapping of researchers, postdoctoral fellows, and students.

Faculty who engage with industry may have different knowledge foundations and abilities to tailor student training appropriate for industry. Recent research, for example, has pointed to the joint labor pool development that occurs though university industry collaborative ties (Lam, 2007). One study of doctoral student socialization indicated that "students believed faculty who have been in industry before have a better sense of industrial needs and problems; see applications more easily; have a useful, down-to-earth perspective; are more able to bring grants because they have more connections with industry; and are more likely to think about commercialization of research" (Mendoza, 2007, p. 80.)

Yet, significant challenges exist, from both, a human capacity as well as institutional capacity perspective, in building effective bridges and mechanisms that allow for this transfer. For students to be attractive employees requires not only the development of strong technical skills or expertise in particular areas of science or engineering, but also a range of other work environment skills that are often outside the scope of traditional STEM disciplinary training (Dunn and Rawlins, 2000). For example, skills in team work, leadership, scheduling of work, coordinating projects, and communication to applied audiences, among other interpersonal skills, are emphasized as important in employability (Knight & Yorke, 2002; Anderson, 2004; Sheppard et al., 2004). Other non-STEM specific skills that address problem solving, and integration of technical issues and user needs are also often pointed to as important for STEM graduates. The challenge to develop the more effective ties with industry and the ability to effectively training students for the industry marketplace has a strong correlation with issues raised above regarding the STEM educational environment. Specifically, the challenge is how to prepare students who seek jobs in industry to develop the skills necessary to not only use their STEM related knowledge and expertise, but also to be competitive regarding other workplace skills (Wye, et al., 2009.)

A significant policy response to many of the issues discussed above has been addressed in the United States by the 2007 America Competes Act (Creating Opportunities To Meaningfully Promote Excellence In Technology, Education, And Science Act.) (H.R. 2272) This bill takes a comprehensive and integrative approach to the range of mentorship and socialization aspects of the scientific process at all career stages. For example, at early pipeline stages, it provides mechanisms to incorporate science mentors in elementary and middle school classrooms. Regarding working scientists, it also specifically requires the U.S. National Science Foundation to incorporate mentoring requirements and plans for any grant that includes a postdoctoral fellow. This deliberately integrated requirement acknowledges the career development aspects of these appointments and placed responsibilities on senior researchers to take their role as senior mentors in this context seriously. These initiatives may be classified as either stand-alone "gap filler policies" where mentoring, and other advisement programs are established to serve as a resource for students and scientists at all career stages, or more integrated approaches where requirements for deliberate mentoring are included within other research initiatives. Generally, mentoring is considered to be a workplace relationship in which the senior or more experienced person (the mentor) provides career related advice and personal support to the junior person (mentee) (Kram, 1985). Knowledge and guidance may be generally related to science as a career, scientific concepts in particular, or preparation for work in various sectors, including industry. Empirical research on mentoring has addressed various mentee outcomes (Noe, Greenberger and Wang, 2002, Allen, Eby, Poteet, Lentz and Lima 2004, Dougherty and Dreher, 2007), and has generally found that mentored individuals, compared to non-mentored, are more satisfied, better rewarded and have less intention to exit. Empirical studies have found that both career mentoring and psychosocial mentoring have an effect on individuals' satisfaction with work and career (Allen et al, 2004), and that career mentoring has stronger effect on overall job and career satisfaction than psychosocial mentoring (Chao, Walz and Gardner 1992). Evidence also shows different benefits realized from mentoring relationships when examined by gender (Kiopa, Melkers, and Tanyildiz, 2008). Given increasing trends in the scientific community to work outside of traditional boundaries, mentors can also potentially play an important role in socializing and training young researchers in working with researchers in other disciplines, other countries, and in other sectors. This type of mentoring and training can have significant benefits, given that younger scientists have been recognized as more open and more easily adaptable to working with colleagues across these types of boundaries.

The America Competes Act reflects a deliberate policy response that seeks to integrate human capacity issues within the context of the educational and research communities. It also underscores that point that in terms of early stages of the pipeline, more than any other issue along the STEM pipeline, addressing challenges specific to youth in science involves a complex set of issues that is fully entwined with education policy and related systems. The most effective policy mechanisms may be integrative approaches that are clearly STI focused but require coordination and engagement with the education community to address educational initiatives, technologies, and classroom level issues. Here, attention to the learning sciences, teacher capacity and preparation, the development and adoption of new learning technologies and other factors are central in addressing these issues.

Increasing the STEM Workforce by Increasing the Participation of Women and Underrepresented Groups in Science and Technology

Considerable attention has been given to attraction, retention and advancement of women in STEM disciplines where globally, the underrepresentation of women is acknowledged as a crisis and significant deficit in most economies. The lack of inclusion of certain groups in science certainly presents important equity issues, but may also be characterized as a "waste" of human resources (NAS, 2007.) Therefore, this **fourth** issue specific to human capacity has relevance at all stages of the STEM pipeline. Building on the general issue of attracting students to the science and technology disciplines, studies have shown that girls are often less attracted, or less encouraged to pursue STEM disciplines. The factors that explain this are multifaceted and range from social, peer or familial influences, to interaction and exposure to role models, to classroom participation, and cognitive or interest related issues specific to science materials. For example, some research has shown that girls may be interested in different scientific questions in their early years, and therefore may be motivated differently in the selection of scientific disciplines (OECD, 2008) and may be deterred from these disciplines by the ways in which science material is presented (Potter and Rosser, 1992; Greenfield, 1995.)

Evidence suggests that increasing the levels of women who advance to earn doctoral STEM degrees is not sufficient, and does not represent the final hurdle to expanding representation in science. In fact, once women have entered STEM workforce, there remain considerable barriers to advancement, productivity, as well as career satisfaction, all of which can also cause departure from science. In response, the academic research community has developed a significant stream of research addressed the attraction, retention, and productivity of underrepresented groups. This literature is important in uncovering key issues and possible areas for remediation and policy response. Studies addressing underrepresentation of women in STEM have explored work environment issues in the academic setting, demands placed on women regarding work-family balances, and the effectiveness of interventions such as faculty mentoring and career development programs (Long and Fox 1995; Levin and Stephan 1998; Rosser 2003; Fox 2005; Levin 2005; Muller, Ride et al. 2005; Leahey 2006). An important issue referenced in much of the gender in science literature addresses the ability of women to identify and access professional and career development networks that are important in career development and success. The lack of inclusion and access to effective networks has been linked to diminished career outcomes for women in science (Rankin, Neilsen, and Stanley, 2007; Realff, Colatrella, and Fox, 2007; Long and McGinnis 1981; Fox 2001; Rosser 2003; Melkers and Welch 2008).

Taking these trends into consideration, the policy community in the U.S., Europe, and the Asia Pacific regions have institutionalized important policy mechanisms that address the building of S&T human capacity among underrepresented groups. These include both “gap filler” policies as well as more integrative approaches to attracting and retaining women in science. One of the most significant programs in the United States is the U.S. National Science Foundation Advance Program (Increasing the Participation and Advancement of Women in Academic Science and Engineering Careers.) This program is deliberately tailored to address the gap of women’s participation in science and has involved more than $130 million dollars in grants since 2001 (NSF, 2010). This is only one of many mechanisms in place in the United States that are designed to address these issues. For example, there are multiple funding opportunities from public funding agencies as well as private foundations to address the interests of girls in science in elementary, middle and high schools, internship programs targeted at women and underrepresented groups at all career stages, mentoring programs for girls and women, among many other initiatives. Integrative approaches that encourage the inclusion of women and underrepresented minorities in funding proposals are also common and relay the message that team diversity is expected.

While women have been a strong focus of these policy initiatives, there remain other important underrepresented groups that have considerable potential to expand the STEM workforce. Depending on the country context, underrepresented groups may include underrepresented minorities, or those who have traditionally had less access to quality education. For example, a critical issue in many settings is that the societal structure in some economies may provide less access to quality education for students from less affluent families, which in turn reflects in the percentage of students engaged in STEM disciplines to increase (OECD, 2008).

Losing and Diminishing Capacity: Brain Drain and Regional Inequities

The size and quality of a STEM workforce may be diminished by a number of factors, including natural attrition due to aging workforces, or issues specific to underrepresented groups, as noted above. However, a significant strain is placed on many economies through the issues of "brain drain", where educated members of the workforce leave their home countries for educational or work purposes, with uncertain prospects of returning. Thus, the **fifth** issue addressed here is the complex issue of brain drain and scientific mobility. For example, the diversity of the STEM faculty workforce in the U.S. is increasingly global in composition, with 28 percent of all doctoral science and engineering faculty and 33 percent of full time science and engineering faculty in research institutions being foreign born (National Science Board, 2008, p. 5-30.) In some fields, this distribution is even more striking – as of 2006, 47 percent of full-time doctoral faculty in physical sciences, mathematics, computer sciences, and engineering employed in U.S. research institutions were foreign-born, many of whom do not hold U.S. doctoral degrees (National Science Board, 2008.) Some European countries report similar figures where a recent study of the United Kingdom and France showed that the proportion of foreign students in doctoral programs in engineering and the physical and natural sciences was close 50% in 1999 (Saravia and Miranda, 2004).

This issue is also a significant policy challenge and one relevant to a number of countries and economies. "Brain drain" is exacerbated in some economies where significant numbers of scientists and engineers leave their home economies to seek employment elsewhere, thereby diminishing the scientific workforce overall. This causes significant strains on home economies, and leaving uncertain futures. Yet, brain drain has also been described a multi-faceted issue, where the in-flow of talent in some jurisdictions, may boost the STEM workforce, thereby providing important benefits to the scientific system and economy overall. However, in some cases, there is concern that this in-flow may also displace the placement, advancement, or retention of a country's nationals. Further, the mobility of scientists has been regarded as an indicator of quality – faculty are recruited or invited as visiting scholars to other institutions because of research productivity and professional visibility. For those who move on their own volition, the ability to relocate is similarly linked to individual productivity.

Scholars suggest caution regarding brain drain issues, as the area depends on both out-flow and in-flow of educated workforce (Davenport, 2004.) As one study noted, "the imposition of barriers to the international mobility of skilled-labor, arguing for instance, that human capital has been partially publicly financed, could end up with opposite effects and result in a decrease in the long-run level of human capital" (Beine, 2001: p. 288). Further, given the increasing global nature of science, brain drain may not represent as much of a departure of talent as may have been traditionally conceived (Davenport, 2004). Approaches that incorporate an understanding of network human capital (Lin, 2002; Bozeman, Dietz and Gaughan, 2001, Davenport, 2004; Melkers and Kiopa, 2010) argue that scientists gain resources through global mobility, and if appropriately mobilized and capitalized, enhances national research capacity. In this, the focus on "brain drain" has been replaced in many contexts with a focus on productive "brain circulation," where the global nature of science is recognized as continuing to return resources to a given economy through the development of knowledge and skills of diaspora scientists and engineers (Meyer, 2001). On one level, it assumes a global "network" of STEM personnel, rather than one that is bounded by national borders (Meyer, 2001). Yet, within this network, some personnel return, bringing and adapting skills, resources, and knowledge to their home environment, thereby contributing to the economy's capacity (Saxenien, 2005). Overall, this "brain circulation" approach acknowledges the range of resources that may be accessed through a circulating global network of scientists and engineers.

While there are U.S. regional issues in this regard, examples of policy mechanisms to address brain drain are mostly non-U.S. based. Globally, various economies have identified this as a significant issue. For example, the Korean government made significant investments over decades to repatriate Korean scientists and engineers (Song, 1997). Similar mechanisms are apparent in many economies where ties with expatriate scientists are encouraged through research funding and fellowship opportunities. Some, like the Korean government, have also established innovative web-based network communities to encourage the interaction of Korean scientists, regardless of place of residence. Overall, these represent deliberate gap-filler policies that in most cases address "brain drain" specifically, but also capitalizing on the resources in "brain circulation."

Related to the issue of brain drain is the **sixth** issue discussed here, regional inequities. Regions with fewer institutional and other resources may be most vulnerable to brain drain and therefore represent a related issue to the discussion above. From a global perspective, this relates to differences across economies, and typically involves the distinction between more and less developed countries. However, for many economies, particularly large ones, within- country regional differences may also be problematic. Some programs therefore have emerged to address geographic or regional differences in research participation or performance. Two parallel examples in the United States are the National Science Foundation Program to Stimulate Competitive Research (EPSCoR) (NSF, 2010b; Melkers and Wu, 2009) and the National Institute of Health IDeA Networks of Biomedical Research Excellence (INBRE) Ideas Program (NIH, 2010). Both of these programs are founded on regional variation in the ability to attract federal research dollars. They are deliberate and integrative approaches to the issue of human capacity by not only targeting less resource-rich areas in terms of scientific labor, facilities, and institutions, but also focus on building human capacity through these initiatives. In both programs, certain U.S. states qualify for participation in the program, by virtue of not reaching certain levels of federal R&D funding. These programs then support a range of mechanisms coupled with research funding to build capacity – including infrastructure but also human capacity. For example, the NIH INBRE program deliberately addresses the development of research and education network across state with the purpose of including faculty and students from less research intensive institutions. NSF EPSCoR also emphasizes state wide participation in the program, often bringing together scientists from different levels of institutions.

Developing Human Capacity in Science in a Broadening Scientific Enterprise

The discussion above addresses the specific career development of individuals as they move through the STEM pipeline. Attention to the development of capacity through training and education is critical. However, capacity issues are also presented within the context of the conduct of science. Thus the final and **seventh** critical issue addressed here is that capacity must develop in light of the increases in global, interdisciplinary, and multi-sectoral collaboration. This has implications at the earlier stages of the STEM pipeline in terms of training and education that led to the development of capacity in later stages among professionals. The capacity to engage in this boundary spanning system and productively participate in it places different requirements on scientists themselves, but also on their training and education, as well as in the systems in which they operate. The role of universities in the production of science, particularly in some economies such as the United States, is significant to the overall research capacity of the nation (Geiger, 2004). Yet, some economies may have better research-related resources, offering increased capacity building resources to scientists and therefore a potentially competitive advantage in developing the capacity and social capital that advance scientific careers. Thus, the contemporary perspective on STI human capacity not only addresses educational and career developmental issues, but also the substantive aspects of preparing for and conducting and research in an increasingly boundary-spanning scientific environment.

Scientific collaboration is increasingly recognized as important for productive and impactful scientific research (Thorsteinsdottir 2000). Overall, it contributes to one's science-related human capital, thereby increasing overall STI capacity. Social capital gained through participation in these collaborative science-based networks can take different forms. Resources such as knowledge, expertise, and equipment are shared and introductions to additional collaborators may be provided through collaborative ties. Therefore, access to and participation with collaborative teams can have important implications for productivity and capacity building in science. In the hierarchy of academe, social capital may also be demonstrated through reputation (Lin, 2004), which is multi-faceted and involves the reputation of the individual researchers and that of their institution.

An important characteristic of today's scientific and engineering environment is that collaboration spans a number of different boundaries. For example, overall, the nature of science and technology is shifting to one where blending knowledge across disciplines is increasingly common. From a conceptual perspective, "multidisciplinarity" is seen as when "elements from different disciplines are present" (Morillo, Bordons et al. 2001), while "interdisciplinarity" not only emphasizes multiple disciplinary dimensions, but also requires "the integration of disciplines within a research environment"(Thi and Lahatte 2003). Thus, interdisciplinary research work is typically achieved either by those researchers who themselves have strong knowledge and expertise in several different disciplines and draw from those disciplines in their work. The value of interdisciplinarity has been well recognized by the scientific community, and reflected in research funding requirements for cross disciplinary interaction. As an illustration, Oliver (2004, p.583) characterized biotechnology as "the industry in which scientific and product development processes are collaborative" and emphasized that "scientific collaborations in biotechnology require collaborations across various institutional settings and disciplines – including between scientists within the same university, between scientists in different universities, and between academic and industrial scientists".

Boundary spanning is not limited to disciplinary traditions. Science is increasingly global, where researchers developed collegial ties across countries and continents. Studies of the scientific enterprise have demonstrated that international research collaboration has intensified over time (Hicks and Katz, 1996, Glänzel and Lange 1997, Glänzel, 2001) where studies have documented increases in the share of internationally co-authored papers, and emergence of the international teams working on similar research problems (Adams, Black et al., 2005, Hicks and Katz, 1996, Luukkonen, Persson et al., 1992). From the U.S. perspective, studies of U.S. scientists have shown increased research team size for the past few decades, while also becoming geographically more dispersed, with a dramatic increase in foreign collaborations, particularly with Asia (Adams, Black et al., 2005.)

Studies of global scientific networks have also observed "preferences" or distinct clusters of collaboration between groups of countries (Glänzel and Schubert 2005; Schubert and Glänzel 2006) where researchers tend to develop collaborative ties with scholars in the same groups of economies. For example, an examination of international co-authored papers from various countries around the world show that the percentage of articles that are co-authored with researchers in the United States ranges from 55 percent (for Taiwan) to Germany (13.5%), the United Kingdom (13.4%), and Canada (11.9%) (National Science Board,2008, p. 5-43).

In building capacity, the "transfer of skills" is an important and primary benefit of research collaboration. Studies of collaborative and other networks in science have pointed to the importance of international collaborative relationships in furthering science overall, but also individual research capacity. Yet, the current infrastructure of science experiences certain challenges in working across these boundaries. Human capacity in the contemporary STI environment must include attention to the barriers to both international and interdisciplinary collaboration (and their combination). From a human capacity perspective, scientists who are better able to work across disciplines and national boundaries will be better positioned to address many of the global and regional scientific problems and challenges that are not discipline specific. From a policy perspective, work in this area can improve the capacity of institutions and research funders to support this type of research. While not discussed here in detail, it is important to note that global collaboration in particular also presents issues of international protection of intellectual property rights, patenting law, and other legal aspects of cooperative science.

Recent policy initiatives to address many of these issues have been primarily integrative and often at the level of funding agencies. For example, in acknowledging the value of cross disciplinary and global cooperation, funders may incentivize these boundary spanning behaviors through funding opportunities or even requirements for cross disciplinary teams. Integration of these incentives, as part of substantive research priorities, highlights support and expectations for scientists to interact in these ways. An issue here, however, places responsibility of the part of institutions to also adapt to the evolving nature of scientific collaboration, particularly regarding interdisciplinary work.

5. CONCLUSION

This paper has reviewed some of the core issues and challenges in developing human capacity in STI. In many ways, it has only skimmed the surface of many of the issues relevant to human capacity in STI given the vastness and complexity of the issues. But, importantly, it has emphasized attention to developing a comprehensive understanding of the components and factors relevant to a discussion of human capacity. In doing so, the STEM pipeline provides a useful foundation for categorizing the barriers and critical factors in developing effective human capacity at all stages of knowledge and career development. It also highlights the interwoven nature of these factors. For example, without strong educational foundations, students are ill prepared to enter and be able to participate in scientific majors as they progress or be attractive to industrial workforce. In another example, without societal support, young people, and especially girls, in some economies may be disinterested or even discouraged from entering scientific and engineering careers.

This paper has also offered a framework for categorizing policy initiatives that target various aspects of human capacity. Here economies are increasingly adopting deliberate "gap filling" policies to target recognized weaknesses or inequities within a given system, region, population, or other group. In some cases, these gap filler approaches are integrated with existing funding and programmatic S&T support mechanisms for the development of human capacity.

From this review, a few policy implications emerge. First, to be effective, policies aimed at enhancing human capacity should not only target interventions at various developmental and career stages, but also acknowledge the interrelationships between those stages along the STEM pipeline. This may lead to increased dialogue between those policy actors who are engaged across the career stages of the pipeline.

Second, the conceptualization of policy instrumentation is also important. While gap-filler policies are useful when well recognized inequities or disparities exist, they may not create change within a system. For example, stand-alone programs to incorporate individuals from disadvantaged regions, or to target a specific group's interest in STEM, may be very effective for that particular area or specified group. However, some capacity development mechanisms may be equally appropriate as embedded within other programmatic mechanisms. For example, the U.S. NSF EPSCoR program has expectations, and related accountability mechanisms, for regional distribution of program benefits and related outcomes within EPSCoR states. So, rather than creating a standalone sub-program that addresses rural campuses, for example, there is an expectation that rural campuses, faculty and students be engaged in EPSCoR grant activities. A deliberate and integrated approach to human capacity development policy can potentially shift national and institutional expectations.

Third, policy interventions should be evidence-based, drawing from prior research on the relationship between key factors that affect capacity development, together with a tailored data and evaluation platform from which to build this evidence-based process. One mechanism for enhancing the effectiveness of human capacity development policies lies in the context of evidence-based policy and decision making. In fact, difficulty of effectively evaluating human capacity development interim and long term outcomes is the final challenge addressed here. The evaluation of capacity is wrought with difficulties, where accurate and appropriate assessment and evaluation of policy initiatives and interventions designed to enhance capacity at various stages of the STEM pipeline requires creative and deliberative evaluative approached. Research capacity is generated from the accumulation of "scientific and technical human capital" (S&T human capital), which is based on not only the education and training of scientists, but importantly, also the resources that they gain through collaborative interactions and ties (Bozeman and Corley, 2004). In the United States, there have been arguments for clearly targeting the measurement of capacity development and related outcomes for programs and initiatives where that is a core goal (Dietz, 2000; Melkers and Wu, 2009.) Yet, capacity is often measured with "arms length" metrics, such as overall research funding received or leveraged, or other measures of productivity. Yet, as addressed here, the issue relevant to human capacity development range from motivational and issues of personal interest, to mastery of material, to barriers to involvement in scientific communities. Thus, in order to develop a clearer assessment of capacity issues and development, an assessment should not only address macro level figures, but also specific data on the development of capacity at the scientist and institutional levels.

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