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Abstract

Many problems of societal importance require researchers from several disciplines to be understood and resolved. As a consequence interdisciplinary research is being encouraged and pursued, sometimes leading to the establishment of new scientific fields. However, interdisciplinary research does not always succeed and it is of importance to not only understand its importance but to also identify the optimal conditions for it to thrive. Further, the benefits of interdisciplinary research and its extent have still not been measured fully.

This document reviews the literature on interdisciplinary research and identifies the key factors for successful collaboration. It looks at the reward structure of interdisciplinary work and ways to encourage it. It then discusses the interdisciplinary structure of energy research which represents an issue of unusual complexity that requires the collaboration of researchers from different disciplines.

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1 INTRODUCTION

Since the 1960s there has been an increased interest in research that crosses disciplinary boundaries amongst policy makers and researchers. It has been recognised that advances in some areas are only possible if skills from different disciplines are brought together and collaborations built, as many problems of societal importance are too complex to be fit into traditional academic disciplines. These collaborations are not only limited to the intersection between disciplines but also include those between applied and basic research interests (Etzkowitz and Leydesdorff, 2000). Hollingsworth and Hollingsworth (2000) analysed the environment in which breakthrough discoveries were made and found that they developed in highly interdisciplinary and integrative institutional cultures. New scientific fields and technologies have emerged at these boundaries such as nanotechnology, genomics, synthetic biology, bioinformatics, and neurosciences.

Universities and funding agents support this development through interdisciplinary degree courses and funding for research that involves researchers from several disciplines. The main reason for this support of interdisciplinary research lies in the expectation that interactions amongst disciplines enhance productivity and creativity (Stirling, 2007) and result in innovation and exploitable applications (Rosenberg, 1982; Foray and Gibbons, 1996). The continuing focus on end-users of research and the push towards research of societal impact further promote research outside traditional disciplinary boundaries. In an experiment, Lakhani et al. (2007) indeed show that the external disclosure of scientific problems proved successful for providing solutions, the majority of which came from scientific fields outside the core discipline. Openness in research, through disclosure and interdisciplinarity, may thus create new opportunities for innovation.

Although the concept of interdisciplinary research is well established and has become a requisite in research policy, we still know little about how to best encourage and maintain successful interdisciplinary collaboration or about its actual benefits. While interdisciplinary research has a long history in non-academic settings where research is usually project driven and team based and transition between departments happens effortlessly, academia faces administrative and cultural barriers and sponsoring difficulties that hinder interdisciplinary research. Many projects carried out under the heading of interdisciplinary research are in fact disciplinary (Weingart, 1997). The nature of the current reward system of science and the structure of the research community obstruct the interdisciplinary research endeavour. Thus, it is not only of importance to create an environment for interdisciplinary research but to also create a system that rewards such collaborations in the long run and helps maintain them.

In this document we will review the existing literature on interdisciplinary research and make suggestions for future studies on interdisciplinary research. In this context we will also look at reward structures and at persistence of interdisciplinary collaboration. Research collaboration in the field of climate change and energy security will serve as a case study to assess the development of interdisciplinary research in an area of pressing societal importance.

The report is structured as follows: Section 2 discusses what we understand as interdisciplinary research, how it is measured and how it can be evaluated. Section 3 looks at the literature on the research collaboration and team science which is closely linked to the discussion on interdisciplinarity. In Section 4 we look at incentives and barriers of interdisciplinary research, and review some empirical studies on risks and rewards associated with non-linear career paths. Section 5 then looks at interdisciplinarity in energy research and section 6 concludes.

2 INTERDISCIPLINARY RESEARCH

2.1 WHAT IS INTERDISCIPLINARY RESEARCH?

The discussion of research that crosses disciplinary boundaries has been very ambiguous in its use of terminology. Multidisciplinary, interdisciplinary and transdisciplinary have been used to describe such research efforts, often interchangeably and with little consensus regarding their definitions. Several papers have looked at the difference in the use of this terminology (e.g. Klein, 1990; Rosenfield, 1992; Choi and Pak, 2006; Tress et al., 2006; Klein, 2010) and concluded that they describe research involving at least two disciplines on varying stages of a collaboration persistence and subject integration continuum. While interdisciplinary research usually shares a common research interest, the level of integration may vary from borrowing and contrasting to integrating and transcending parts of two or more disciplines (Miller, 1982), as does the stability of the cross-disciplinary research effort (see Table 1). However, Klein (1990) stresses that there is no automatic progression between different stages.

TABLE 1: TERMINOLOGY OF INTERDISCIPLINARY RESEARCH

Unidisciplinary	discrete	preservation of discipline
Multidisciplinary	additive, collaborative	preservation of discipline
Interdisciplinary	integrative, synthesis, convergence	emergence of inter-discipline
Transdisciplinary	holistic	transcend disciplinary perspectives

The different terms used in the literature are not conclusive when it comes to describing the exact nature of interdisciplinary research. They contain no information on the modes of participation, i.e. whether it is a team or single researcher effort and whether external stakeholders are involved, and no information on the level of boundary crossing, i.e. whether disciplines are already overlapping or close. Klein (1990) therefore criticizes the use of different labels (terminology) for interdisciplinary research and also argues that the conflicting meanings of interdisciplinarity in the literature make the term little adequate (see Klein, 2010 for a review of existing categorisations). Rafols and Meyer (2010) therefore prefer to describe interdisciplinarity in terms of *diversity* and *coherence* which more accurately describe the integration of different types of knowledge. Klein (1990) also contests that a typology that looks at the why, what and how of interdisciplinary research is more apt. This chapter follows Huutoniemi et al. (2010) in their typology to discuss the different types of interdisciplinary research.

2.1.1 MOTIVATION FOR INTERDISCIPLINARITY (WHY)

An important aspect of interdisciplinarity and the one that shapes its structure and scope are its underlying goals and motivations, including potential beneficiaries (Bammer, 2008). Huutoniemi et al. (2010) argue that interdisciplinarity is driven by specific research goals that demand new approaches outside traditional boundaries and differ between *epistemologically* and *instrumentally* oriented research that is addressed through interdisciplinarity.

Epistemologically oriented research is driven by a desire to understand the complexity of society and nature and interdisciplinary approaches are sought as they are "expected to lead to a more profound scientific understanding or more comprehensive explanations of the phenomena under study" (Huutoniemi et al., 2010: 88). Klein (2010) labels this *critical* interdisciplinarity arguing that it questions existing knowledge structures with the implicit goal of transforming them. Blackwell et al. (2009) prefer the term *curiosity-driven* research. Through a combination of different disciplines new insights can be gained and may serendipitously result in knowledge breakthroughs (Blackwell et al., 2009). Interdisciplinarity in this context thus primarily arises out of the desire for knowledge and understanding without the specific intention of developing something new. It occurs when researchers search for new promising areas that could lead to significant new findings (Gieryn, 1978).

Instrumentally oriented research, on the other hand, is application oriented with a focus on solving real world problems or achieving a commercial goal (Huutoniemi et al., 2010). These include the focus on societal issues like cancer, climate or terror and commercial goals. They are thus often initiated as a reaction to political controversies (Bammer, 2008) and market demands. Interdisciplinary approaches are expected to better address policy or market demands with a direct focus on user engagement. Blackwell et al. (2010) label this *outcome-driven* research with the specific goal of solving practical problems and driving innovation. Several policy reports have stressed the importance of collaboration and interdisciplinarity for innovation arguing that it enables technology development and scientific breakthrough (see HM Treasury). As a consequence several funding bodies now actively push for increased involvement in interdisciplinary research as well as research involving end-users and external stakeholders (e.g. RCUK, 2006; NSF, 2006; EC, 2007; ESRC, 2013). Additionally, interdisciplinarity may be instrumental in making science more accessible by improving its communication with the wider publics, thus assisting the accountability of research (Barry et al., 2008). This can be seen in collaborations between art and science where art can help communicating abstract scientific ideas. Such instrumentally oriented interdisciplinary research often implies borrowing methods or tools from other disciplines without the further intention to integrate these (Klein, 2010). However, it can go beyond simple borrowing in an attempt to provide comprehensive answers, solutions and services and result in scientific areas like ergonomics or biotechnology.

The distinction between the two approaches is not absolute and many projects combine the improvement of scientific understanding with a focus on societal or technological problems. Huutoniemi et al. (2010) label this a *mixed* orientation. Blackwell et al. (2009) name several examples of curiosity-driven research resulting in applications (e.g. DNA fingerprinting) as well as outcome-driven research leading to results other than those anticipated.

2.1.2 SCOPE OF INTERDISCIPLINARITY (WHAT)

As pointed out by Klein (1990, 2010) not all interdisciplinary research is the same. Much of the research labelled interdisciplinary crosses boundaries where disciplines already overlap or are close. She refers to this as *narrow* interdisciplinarity. Fields involved in such narrow exchanges are part of the same scientific area e.g. natural sciences. As Huutoniemi et al. (2010) point out, exchanges between such related fields are not uncommon and already well-established due to related theories, methods and dissemination norms. On the opposite end of the scale Klein considers *wide* or *broad* interdisciplinarity. Here disciplines from different traditions cross boundaries and integrate knowledge from outside their core areas for example integrating genetics and music. Huutoniemi et al. (2010) stress that broad interdisciplinarity is difficult to achieve as there is little compatibility between fields and new methods or theories have to be accepted.

Huutoniemi and co-authors caution that not all collaboration between perceived distant disciplinary areas has to be interdisciplinary as distant "domains of scholarly work also have cognitive overlaps" (2010: 84). At the same time, many established disciplines are internally divided and interdisciplinary research can happen within the boundaries of disciplines (Barry et al., 2008). Boundaries of disciplines and between disciplines are thus continuously being questioned (Barry et al., 2008). Rafols and Meyer (2010) therefore prefer the term cognitive diversity to describe interdisciplinarity. They contest that knowledge integration happens without necessarily breaking down disciplinary boundaries and that the concept of cognitive diversity accommodates interdisciplinarity within and beyond established disciplines. Also Mulkay (1974) suggest a wider approach to interdisciplinarity as a collaboration of researchers from different research networks.

Klein (1990, 2010) pointed towards the existence of disciplines that are more open towards interdisciplinary research. Unrestricted disciplines, which include most social sciences, are described as open to outside disciplines (Pantin, 1968). They could be considered less codified and more fragmented, allowing for influences from other research areas. Applied fields with a vocational element, like engineering or medicine, can also be considered more integrative and as intrinsically interdisciplinary due to their wider scope (Heckhausen, 1972). Restricted disciplines, on the other hand, show fewer ties with other disciplines, a higher level of codification and have a more consistent theory (Pantin, 1968). The physical sciences and economics could be considered such closed disciplinary areas. This is supported in studies by Rinia et al. (2002) and Crane and Small (1992). Rinia et al. (2002) analyse cross-citation patterns in different scientific fields and find that physical sciences have high levels of self-citations but weak ties with other disciplines, while psychology and engineering have low levels of self-citations (see Table 2). Rinia et al. (2002) also investigate subfields of Physics and find that instrument or material based research areas, like microscopy or crystallography are more interdisciplinary than theoretical fields like nuclear physics or particle physics. These structures are relatively persistent across time as shown by Porter and Rafols (2009). Crane and Small (1992) looking at social sciences, showed through citation pattern analysis that economics has a strong disciplinary structure, while sociology is lacking a universal theory and draws from other fields, including economics.

TABLE 2: SHARES OF REFERENCES PER DISCIPLINE IN THE WORLD TOTAL OF PUBLICATIONS 1999
Numbers and shares are based on weighted numbers of references (Source: Rinia et al., 2002)

	Percentage references to:																Weighted number of
Cited discipline (j)	Basi	Biol	Chem	Clin	Comp	Engi	Envi	Food	Geo	Mate	Math	Mult	Phar	Phys	Psyc	Total	ref's
Citing discipline (i)																	
Basic Life Sciences	**62.9**	2.6	1.6	15.0	0.1	0.1	0.3	1.9	0.1	0.1	0.0	11.5	2.3	0.5	1.0	100	110844
Biology	31.4	**35.8**	1.0	5.1	0.1	0.2	8.3	5.4	1.4	0.1	0.4	7.9	1.0	0.5	1.3	100	21534
Chemistry	7.4	0.5	**63.2**	2.7	0.2	1.3	0.9	1.7	0.7	4.9	0.1	2.8	1.3	12.3	0.0	100	71082
Clinical Life Sciences	22.2	0.6	0.6	**66.9**	0.1	0.4	0.1	1.2	0.0	0.1	0.1	4.9	2.1	0.3	0.5	100	149403
Computer Sciences	5.8	0.8	2.4	3.0	**45.3**	19.2	0.5	0.3	1.1	0.5	10.0	2.5	0.2	7.9	0.6	100	15102
Engineering & Technology	2.8	0.5	5.1	6.7	5.2	**39.1**	3.4	1.2	3.7	6.2	2.6	1.4	0.3	21.5	0.1	100	31808
Environmental Sciences	7.1	12.9	4.0	2.8	0.1	3.8	**44.5**	6.9	9.6	0.3	0.3	4.1	2.4	0.7	0.5	100	15058
Food, Agricult. & Biotechn.	26.0	7.1	3.8	14.7	0.1	0.6	4.1	**35.0**	1.4	0.5	0.1	4.4	1.5	0.3	0.4	100	28291
Geo Sciences	1.0	1.8	1.8	0.2	0.3	2.8	6.6	1.5	**69.8**	0.5	0.2	7.2	0.1	6.1	0.0	100	19417
Materials Sciences	1.3	0.1	14.8	1.4	0.2	5.2	0.2	0.7	0.7	**49.4**	0.1	2.3	0.2	23.6	0.0	100	34528
Mathematics	1.3	1.7	0.5	1.5	4.9	5.6	0.4	0.2	0.5	0.3	**72.9**	1.2	0.1	8.8	0.1	100	19479
Multidisciplinary Sciences	45.5	4.0	2.2	10.0	0.2	1.0	1.3	1.7	3.9	0.8	0.6	**20.1**	1.4	6.7	0.6	100	9622
Pharmacology	31.7	1.2	3.3	29.0	0.1	0.3	1.6	1.6	0.1	0.2	0.1	5.4	**23.2**	0.2	2.1	100	16218
Physics	1.5	0.1	6.4	0.7	0.4	3.5	0.1	0.1	1.5	3.5	0.5	2.8	0.1	**78.8**	0.0	100	95435
Psychology & Psychiatry	33.8	4.7	0.1	16.4	0.2	0.2	1.4	1.0	0.0	0.0	0.1	5.1	8.1	0.3	**28.5**	100	6095
Total	21.6	2.8	9.9	21.0	1.6	3.8	2.2	2.9	3.1	4.1	2.7	5.4	1.9	16.3	0.7	100	643916

In unrestricted research areas, which are open to outside disciplines, interdisciplinary research increases quicker than disciplinary research, which may result in a decay of traditional disciplines. For example, the increased fragmentation of disciplines like sociology led to a lack of a coherent theory that speaks to major issues in the field (Crane and Small, 1992). As a consequence it is rapidly disappearing as a discipline and gets embedded in other areas which results in a crisis for sociology researchers that move their attention away from the core to subfields like media, science and religion (Crane and Small, 1992), and in a crisis for sociology as a scientific subject.

The concept of scope, can further be extended beyond the simple framework of scientific fields. Aspects of interdisciplinarity are found in research that crosses historic and geographical boundaries, involves different levels of analysis or combines a set of different methodologies, technologies or materials (Bammer, 2012). Further, different social sectors may be involved in joint research with broad interdisciplinarity involving more diverse sectors (Klein, 2010). In fact, previous research has shown that researchers that engage in interdisciplinary research are also those more likely to collaborate with external stakeholders.

2.1.3 STRUCURE OF INTERDISCIPLINARITY (HOW)

As already mentioned above, the types of interactions between fields differ from project to project. While some interdisciplinary research projects pool knowledge from different disciplines without integrating these into new theories or even requiring the participation of researchers from different fields, others develop new theoretical tools creating generic links between disciplines (Huutoniemi et al., 2010). Klein (2010) and Huutoniemi et al. (2010) propose a set of classifications for different levels of interdisciplinary interaction from weak to full forms of interdisciplinarity. The most elementary form of interdisciplinarity they call *encyclopedic* which describes research that consists of several sub-projects linked by a common topic but without any cognitive interaction between the fields. Many interdisciplinary research projects are in fact characterised by such "false" interdisciplinarity that involves no communication between sub-projects (Klein, 2010). Interdisciplinarity is entirely additive in such projects.

Klein (2010) further defines interdisciplinarity that is *contextualizing*, providing a common framework that requires an interdisciplinary approach. However, the separate research groups work independently and do not interact and findings are not integrated. Such projects appear interdisciplinary on the surface but fall back into disciplinarity (Klein, 2010; Huutoniemi et al., 2010).

On the other end of a non-integrative scale Klein (2010) and Huutoniemi et al. (2010) describe *composite* approaches that are characterised by technical integration, for example through borrowing approaches from other fields, but through less conceptual integration. These can be seen as exchange interdisciplinarity with no direct interaction.

Interdisciplinary approaches that partially integrate different fields are labelled *empirical* or *methodological*. Different technologies, materials and data are shared or approaches to a shared research problem are being employed to either develop methodologies or to allow for the triangulation of data sources and methodologies (Huutoniemi et al., 2010).

Finally, full or "true" interdisciplinarity is labelled *theoretical*, and describes a research project that integrates concepts and methods from different fields to develop generic links and provide new theoretical models and knowledge (Klein, 2010; Huutoniemi et al., 2010). Thus, disciplines do not just need to interact but need to converge to be truly interdisciplinary.

Rafols and Meyer (2010) call this classification from weak to full forms of interdisciplinarity *coherence* of the interdisciplinary network. Coherence in this context measures the structure and intensity of interactions, i.e. the extent to which concepts and methods used in the research project are related (Wagner et al., 2011). An increase in coherence indicates a closer link between disciplines. Figure 1 places the identified structures on a coherence graph.

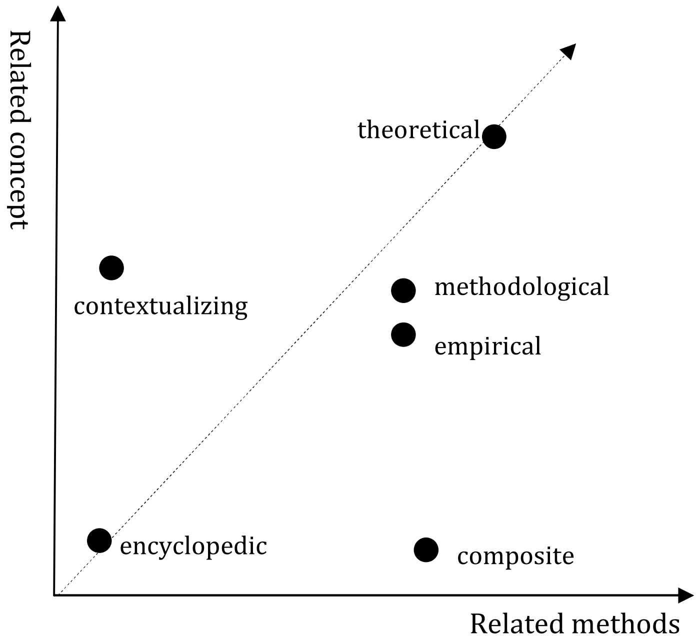

FIGURE 1: STRUCTURES OF INTERDISCIPLINARY RESEARCH PROJECTS
Source: (Klein, 2010; Huutoniemi, 2010)

2.2 MEASURING INTERDISCIPLINARY RESEARCH

Policies promoting interdisciplinary research have been widespread in recent years, despite the little empirical evidence regarding its benefits. There are only a few studies comparing disciplinary and interdisciplinary outcomes or how such collaborations are formed (Jacobs and Frickel, 2009). The reasons that evidence on interdisciplinarity is still scarce are the difficulties in defining success and the difficulties in finding consistent measures for interdisciplinary research (Huutoniemi et al., 2010). Further, the measure of analysis and the level of integration need to be defined to build useful indicators (Wagner et al., 2011). Different approaches to measuring interdisciplinarity and success are reviewed in this chapter.

2.4.1 BIBLIOMETRIC MEASURES

Scientific outputs have traditionally been used to create indicators for science studies and are also common for the operationalization of interdisciplinary research, though they remain controversial (Huutoniemi et al., 2010; Wagner et al., 2011). Bibliometrics uses a variety of different measures for interdisciplinarity, including such based on keyword analysis, subject categories of the published article or subject categories of citing or cited articles. Most rely on the subject categories provided by the Web of Science. Further, they use different methods for calculating interdisciplinarity measures and different levels of analysis, e.g. individual academics, research groups, articles, journals or scientific fields. Research that looks at the article as the level of analysis uses the number of different subject categories on an article, a diversity indexes of subject categories, the proportion of citations to or from other scientific fields or more complex cross-citation network indicators (Rafols and Meyer, 2010; Wagner et al., 2011). On the level of the individual researcher possible measures include the proportion of papers published outside the academic's main field of interest, diversity indexes of subject categories or keywords of the article or its citations, and disciplinary affiliation of co-authors (Leahey, 2007; Wagner et al., 2011; Yegros et al., 2013).

All these measures have as a premise that research interests can be measured through scientific publications (or patents) and rely heavily on subject categories provided by the Web of Science (or other databases). Both have been contested as firstly not all research results in bibliometric outcomes and interdisciplinary research groups may choose to publish discipline-specific articles. Secondly, subject classification does not accurately reflect interdisciplinarity. In the case of engineers, their research may be applicable to a wide range of different subject areas and does not indicate interdisciplinarity in itself. Finally, interdisciplinarity measures based on citations do not necessarily reflect the interdisciplinarity of the respective researchers. While management scholars for example may cite mainstream economists, they remain strictly within management themselves.

Thus, there are several limitations to bibliometric measures, especially those based on WoS subject categories. Content or keyword analysis of articles to identify interdisciplinary research lines are still not widely spread and limited to small sample studies as they are difficult to manage due to data and software limitations.

2.4.2 OTHER QUANTITATIVE MEASURES

In addition to outcome based measures some researchers have used funding data to observe interdisciplinary teams (e.g. Cummings et al., 2013). Research funders like the National Science Foundation (NSF) in the US, the EU, or the UK research councils award grants to individuals or teams. If teams are funded their members may belong to different scientific disciplines or sub-disciplines and be used as a measure for interdisciplinary collaboration. While this is an approach that enables us to observe an interdisciplinary research group ex-ante they do not give information about the actual level of interaction within the project. Research groups may form to increase their likelihood to receive a grant but researchers may then work independently on parts of the project without direct interaction. The measure is therefore only useful in combination with bibliometric measures. Rhoten and Parker (2004), to avoid this problem, only looked at grants awarded as part of an interdisciplinary research programme. However, in limiting the sample to interdisciplinary research, it is not clear how their findings compare to unidisciplinary projects.

Other studies have employed surveys and asked researchers directly if and how often they participated in interdisciplinary teams (e.g Rhoten and Pfirman, 2007; van Rijnsoever and Hessels, 2011). Such studies, however, do not allow a long-term analysis and often do not investigate the quality of the interdisciplinary project.

Finally, some studies have used interdisciplinary research degrees as an indicator for interdisciplinarity (e.g. Millar, 2013). Such studies are particularly aimed at investigating early research productivity or career advancement but do not give indication on whether interdisciplinary research lines are also pursued later in the career or if such interdisciplinary trained researchers are better equipped to join interdisciplinary teams.

2.4.3 QUALITATIVE MEASURES

To overcome the limitation of quantitative studies several authors have instead relied on qualitative assessment of interdisciplinary projects through observation, interviews or project and evaluation report analysis (e.g. Bammer, 2008, 2012; Hollingsworth and Hollingsworth, 2000; Huutoniemi et al., 2010; Stokols et al., 2008). These studies provide crucial insights into group dynamics and into different levels of interdisciplinarity but are mostly limited to small case-studies. Richard Hollingsworth discusses in several publications results of a study of 291 major discoveries (Hollingsworth, 2008). Through intensive interview and archival work he analysed the organisational context in which these discoveries occurred, as well as a control sample of institutions where major discoveries did not occur. Based on this in-depth analysis he drew conclusions on the interdisciplinarity of breakthrough discoveries. His study is important for understanding the dynamics in which interdisciplinary research happens.

2.3 EVALUATING INTERDISCIPLINARY RESEARCH

The above discussions of different types of interdisciplinary research as well as potential measures lead us to the final important question, the evaluation of interdisciplinary projects. The evaluation of interdisciplinary research presents a problem for policy makers and social science researchers due to the complexity of interdisciplinary projects and goals (Klein, 2008). Bammer (2008, 2012) and NSF (2004) therefore suggest evaluating projects based on the typology discussed in section 2.1:

(1) Have the different goals that motivated the interdisciplinary research been achieved?

(2) Was the interdisciplinary mix and scope appropriate for the research question?

(3) Have the methods and concepts used been effective for the suggested research question?

Additionally, other, perhaps unintended outcomes could be generated through the interdisciplinary project that enhance or damage the original goals of the research. In their report, NSF (2004) point out several indirect benefits associated with interdisciplinary research, which include:

(1) increases in institutions' reputation,

(2) increases in teaching quality,

(3) increases in scientific network diversity,

(4) demonstration of the applicability of methods or instruments in several scientific fields,

and which can be added to an evaluation.

In this context of project specific evaluation Bammer (2008, 2012) points out that no single, perfect solution exists, but that each institution, funding body or research group may define their own criteria. Klein (2008) concludes that "variability of goals drives variability of criteria and indicators" (p. S121). Such requirements make the use of just one method for evaluation unviable. Stokols et al. (2008) rightly point out that: "the combined use of survey, interview, observational, and archival measures in evaluations of team science initiatives affords a more complete understanding of collaborative processes and outcomes than can be gained by adopting a narrower methodologic[al] approach" (p. S82).

However, such complex measures are difficult to produce and thus not very useful as indicators in science studies (Wagner et al., 2011). Therefore many researcher and policy makers rely on bibliometric measures including statistics on publications, citations, patents and grants. Yegros et al. (2013) for example find that interdisciplinary publications receive more citations than disciplinary ones. However, there is a threshold in the level of interdisciplinarity beyond which marginal returns in terms of citations decrease. They conclude that interdisciplinary research publications are more visible than disciplinary ones, perhaps because they are of interest to more than one disciplinary field. Larivière and Gingras (2011) looking at all articles published in Web of Science in 2000 confirm these findings but suggest that an optimum degree of interdisciplinarity could exist. While such studies provide a first analysis of the benefits of interdisciplinary research, they are subject to an assessment based on discipline-specific measures (Martin and Whitley, 2010). Peer-review, as will be discussed in more detail below, is still dominated by a disciplinary perspective even in the case of interdisciplinary grant evaluation panels (Mallard et al., 2009). Further, by relying on quantifiable outputs other impacts of interdisciplinary research remain uncovered. Wagner et al. (2011) point out that this is particularly problematic "as the extent of this gap is unknown" (p. 20).

3 COLLABORATION IN SCIENCE

Neither the classification proposed by Klein (2010) nor the definition of interdisciplinary diversity and coherence (Rafols and Meyer, 2010) require the presence of teams. Interdisciplinary integration can happen through teams or individuals (Porter and Rafols, 2009) and can involve external or only internal stakeholders. Though Porter and Rafols (2009) rightly point out that true interdisciplinarity requires single researchers to integrate different disciplinary approaches, collaboration plays an important role in achieving this. Team members bring together a set of different skills and concepts that can form the basis for interdisciplinary research and innovation. Bammer (2008) summarizes the motivations for collaboration as bringing together research partners with diverse characteristics that are relevant for addressing the research problem. Prominent examples for large team based interdisciplinary projects are the Manhattan Project or the Human Genome Project.

Teams have always played an important role in scientific research. For example, Zuckerman (1967) found that Nobel Laureates are more likely to work in teams than a matched sample of researchers. Since then the amount of research done in teams increased dramatically (Wuchty et al., 2007; Jones et al., 2008). Jones (2009) argued that researchers experience an educational burden that is compensated through longer training and increased specialisation, thus requiring more teamwork. Empirically he shows evidence for longer training and increased teamwork over the past three decades. Katz and Martin (1997) point at the increased costs of research as an incentive for collaborative projects, while the decrease in travel and communication costs has further enabled collaboration. The new field of science of team science tries to understand the effectiveness of such collaborations and the consequences of increased specialisation (Stokols et al., 2008).

This chapter discusses the literature on team science and collaboration, identifying the drivers and hurdles associated with collaboration in general and, more specifically, with interdisciplinary teams.

3.1 PATTERNS OF COLLABORATION

Science does not evolve in isolation but is a product of a large scientific community that relies on prior knowledge. As Subramanyam pointed out: "[e]ven the secluded solo researcher is indebted to his forerunners" (1983: 33). Subramanyan (1983) provides a list of types of collaborations where two or more researchers work together on a joint project contributing with both, resources and effort. This definition specifically excludes sponsor relationships as these do not necessarily involve collaboration. The first type of collaboration defined by Subranmanyan (1983) relates to a teacher-student relationship or alternatively a supervisor-assistant relationship. In these, a professor provides the grants and students or assistants carry the majority of the research task. Collaboration is limited to a professor's supervision of varying degrees. A second type of collaboration is research collaboration amongst colleagues. Research collaboration is often limited to specific projects, often with members contributing to different aspects of the project. Gibbons et al. (1994) argue that such research project collaboration is a characteristic of the new 'mode 2' knowledge production that requires more interdisciplinary teams to come together for specific problem-driven research. Research collaborations occur within the same institution but also across organisations, sectors and countries.

Subranmanyan (1983) further writes that collaboration can take many forms from plain advice to active participation in a research project. Using such a broad definition, collaboration already occurs through informal exchanges between scientists. Just as we discussed above in relation to interdisciplinary integration, collaboration can be limited to an exchange of data or can describe the work of group members on parts of a larger project. Some disciplines are more likely to involve collaboration, and experimental work requires more collaboration than theoretical work with big science requiring the largest group effort (Katz and Martin, 1997).

Further, spatial proximity is an important element of collaborative research as it encourages informal exchanges that form the basis for later joint research (Katz and Martin, 1997). Several authors have shown that firms are more likely to collaborate with local universities (Audretsch and Stephan, 1996; Mansfield and Lee, 1996). Also researchers are more likely to collaborate if they are spatially close (Hollingsworth and Hollingsworth, 2000). However, since the 1990s better telecommunication technologies and cheaper airfares have reduced the barriers for more distant collaboration (Katz and Martin, 1997; Ding et al., 2010). This has also led to a decline in the importance of research labs that previously benefitted from co-location (Hollingsworth and Hollingsworth, 2000)

3.2 EFFECTIVENESS OF TEAM SCIENCE

Collaboration between individual researchers has been assumed to represent a powerful mean for advancing knowledge (Katz and Martin, 1997). There have been several policy initiatives to bring together researchers in collaborative teams, for example through the provision of large research centres like CERN. Collaboration is not only associated with increased innovation and commercial impact, but can also allow for cost saving (Katz and Martin, 1997). Higher collaboration levels have repeatedly been shown to be positively correlated with productivity (both publication and patents) and larger teams tend to be more influential and more highly cited (Katz and Martin, 1997).

The growing interest in collaborative research and large, team-based research projects led to the question of how to best facilitate collaborations. As Bammer (2012) points out, there is no golden bullet for success. Each collaborative project is different and characterised by a range of unpredictable factors. Further, perfect solutions may not exist. While collaboration can be beneficial to research efforts by utilizing the different attributes of team members, Bammer (2008) points out that they can result in 'unproductive conflicts'.

Factors that have widely been seen as crucial for team research are "sustained and intense communication" between team members and "talented leadership" (NAS, 2004: 19). Building relationships to understand concepts and methods used by other researchers and research areas are crucial as is a team leader with experience in managing diverse groups. Hollingsworth and Hollingsworth (2000) analyse the drivers of breakthrough discoveries in the 20th century. They find that leadership that is aimed at integrating diverse disciplines and that has the ability to move research in that direction is more likely to lead to important discoveries. At the same time, communication problems due to different traditions and vocabulary require the use of bridging agents in collaborations that span different disciplines or sectors. Further, a clear joint goal needs to be specified to lead the research group effort. These elements all mostly come down to personal characteristics and interpersonal skills of team members. Teams that assemble a larger number of similar researchers face fewer conflicts and fewer difficulties in their communication and coordination than more diverse teams, however, they are also less creative (Hollingsworth and Hollingsworth, 2000).

Secondly, team success is more likely to be achieved if researchers have the opportunity to pursue their own goals within the framework of a collaborative project. In the case of collaborations between industry and science, university researchers may want to pursue publication of research while firms favour patents. In interdisciplinary research projects, researchers from different fields may favour different outlets for their research work to make maximum impact. Such different field or sector specific output requirements or goals need be discussed in advance and enabled for a collaboration to be successful for all participating parties. Thus, acceptance of respective goals, potentially manifested in research contracts, are important for keeping a collaboration intact and to ensure maximum impact (NSF, 2004; Bammer, 2008).

Finally, organisational support is essential for successful collaboration to happen. Mechanisms to incentivise and reward collaboration need to be put in place. These include rewards in terms of career progression and seed funding to enable exploration of potential partnerships. The report of the National Academy of Science (NAS, 2004) further points out the importance of funding agents and organisations to sponsor and support risky projects and to award appropriate time to collaborative projects. This is not unique to the success of collaborative projects but any innovative research endeavour. In a recent paper Azoulay et al. (2011) study the impact of funding from two different public sponsors with different grant design and agenda. They find that funding from the Howard Hughes Medical Institute's, a sponsor that allows for more scientific freedom, perform significantly better than a group of similar researchers funded by the National Institutes of Health (NIH). Organisational support can further extend to the provision of joint facilities, e.g. dining areas, which encourage communication (Hollingsworth and Hollingsworth, 2000).

While all these success factors apply to all forms of team research, they are particularly crucial for interdisciplinary projects. Communication and coordination requirements are higher than for projects that only involve one disciplinary field. Also, defining common goals and making space for individual goals is more complex. These require specific individual skills as well as commitment at the personal level. Such commitments are affected by incentive and reward mechanisms, which, however, are not fully developed and are in conflict with other research and training based evaluations. The next chapter addresses this issue in relation to interdisciplinary research.

4 REWARD STRUCTURES FOR INTERDISCIPLINARY RESEARCH AND CONSEQUENCES FOR CAREER PATHS

This chapter reviews incentive and reward structures put in place for interdisciplinary research and outlines some of its consequences. It relates this to other, potentially competing incentives that may affect interdisciplinary research and its success.

4.1 INCENTIVES AND BARRIERS FOR INTERDISCIPLINARY RESEARCH

4.1.1 FUNDING BODIES FACILITATING INTERDISCIPLINARY RESEARCH

A range of financial rewards have been made available both at the level of the university and through funding bodies. The structure of disciplines and relationships between them is heavily influenced by national funding regimes (Lyall and Fletcher, 2013). National funding bodies are in a particularly powerful position to influence interdisciplinary relationships through their management of boundary spanning projects and programmes (Lyall et al., 2013). For example, in the UK government funding bodies now actively push for increased involvement in interdisciplinary research (e.g. RCUK, 2006, ESRC, 2013) and have identified a range of priority programmes that require interdisciplinarity (Lyall and Fletcher, 2013). They push for institutional structures to change by, for example, establishing interdisciplinary research centres. Also charities have made funding available specifically aimed at promoting interdisciplinarity. One such example is the Wellcome Trust's Sciart programme established in 1996 and replaced by the Arts Award in 2006 supporting art's involvement with science. Also the European Union supports research across countries, disciplines and sectors through its seventh framework programme (EC, 2007), reacting to the significant policy attention given to interdisciplinary collaboration.

4.1.2 UNIVERSITIES FACILITATING INTERDISCIPLINARY RESEARCH

In addition universities have the role to facilitate team formation, for example through the establishment of a management position and the creation of a central organisation unit for interdisciplinary research that helps bring together researchers from different areas and bridge between them. Hollingsworth (2008) finds that laboratories that foster interdisciplinary research are less hierarchical and have lower levels of department differentiation. Catalini (2012) has shown in a natural experiment that random co-location of different departments help increase the level of collaboration between these. Further, random co-location of distant scientific fields results in more impactful collaborations than random co-location of close scientific fields. This result suggests that universities can play a role in increasing interdisciplinary research by reducing the distance between researchers, e.g. by providing shared facilities. Small private institutions in the US quote their canteens as an important place for networking, but this is less of an option for large universities (Hollingsworth and Hollingsworth, 2000). Universities can instead establish interdisciplinary centres and provide seed funding for projects to encourage collaboration across fields (NAS, 2004). Further, training courses to enable researchers to communicate their research across disciplinary boundaries and to sensitise for research language outside their core research could also be offered. Another approach is to offer education and research stays in distant research fields to allow researchers to train in a new field. Universities should also reward interdisciplinary efforts in terms of promotion advantages and the recognition of alternative career paths.

As a successful strategy for the future, funding bodies and universities are supporting interdisciplinary PhD programmes. Here students find themselves being evaluated by committees whose members come from various disciplines. Such interdisciplinary PhD programmes may train a new generation of interdisciplinary scholars endowed with the skills to work across disciplinary boundaries (Lyall et al., 2013).

4.1.3 BARRIERS TO INTERDISCIPLINARY INITIATIVES

Thus, through research funding many scientists now find themselves in interdisciplinary teams or projects (Lyall and Fletcher, 2013), however, such financial support does not necessarily suggest institutional support. Disciplines are strongly embedded in the university structure and while these borders are broken up for specific projects, they do not prevail. Several institutions are attempting structural and strategic changes by, for example, abolishing and restructuring departments, with mixed success. In an interview Hollingsworth therefore concludes that "It's easier to establish a new research organization than it is to change an older one." (Whitfield, 2008).

Some universities have established interdisciplinary research centres but their future is often uncertain and they are usually embedded within existing disciplinary frameworks. The problem of establishing permanent centres for interdisciplinary research are also due to the fact that interdisciplinary teams are formed for specific research projects and broken up and new teams formed when new projects are started. Further, all these initiatives are often accompanied by diverting resources from other activities and may lead to unproductive competition.

While research funders promote interdisciplinarity, their organisational structure and reviewing system is based in traditional disciplines. In the UK, the historic division of British research councils by subject areas leads to difficulties in allocation at the boundaries between fields. Also, block funding is allocated based on traditional disciplines. In the UK the Research Excellence Framework (REF – previously the Research Assessment Exercise (RAE)) upon which quality related funding allocation is based, requires submission of research and staff details in pre-defined disciplinary subjects. The submission process also allows each grant or publication to only be submitted once and in one subject even if it spanned several disciplines. Through this it indirectly supports the preservation of disciplines. This has caused tension between departments as illustrated in an article in Nature in 2008 where researchers in Imperial College struggled over the division of funding and credit. REF produces incentives for research groups and departments to be "selfish" (Whitfield, 2008).

Another barrier is departments' tendency to reproduce themselves (Hollingsworth and Hollingsworth, 2000). As academic departments grow they tend to hire staff with similar characteristics and backgrounds. In doing so, diversity and creativity are reduced. Thus, more flexible assessments and organisational structures are necessary to reward interdisciplinary efforts on a permanent basis while controlling growth.

4.2 RISKS AND REWARDS OF INTERDISCIPLINARY RESEARCH

While the wider benefits of interdisciplinary research have been acknowledged by policy makers and scientists alike (Jacobs and Frickel, 2009), and factors that facilitate interdisciplinary research have been identified, they do rarely consider individual professional implications. Rhoten and Parker (2004) find that while younger researchers are more likely to be involved in interdisciplinary research, exploiting research opportunities at the boundaries (Sung et al., 2003), they are also more likely to state negative career effects in the long-term.

They acknowledge short-term benefits of interdisciplinary projects, which provide interesting opportunities in project work, but may lead to difficulties in achieving tenure (Rhoten and Parker, 2004). Millar (2013) in an analysis of the Survey of Doctorate Recipients in the US shows that interdisciplinary trained graduates are more likely to take up a job in academia, however, there is some indication that they take longer to be awarded a tenured position. Also van Rijnsoever and Hessels (2011) find in a survey of academic staff at a Dutch university that while disciplinary collaboration contributes positively to career progression, interdisciplinary collaboration does not. Thus, while some short-term benefits in terms of access to interesting research projects may exist, researchers with an interdisciplinary research background “face the challenge of finding departments that feel that the candidates “belong” with them” (NAS, 2004: 69). In a survey undertaken by NAS (2004), respondents list tenure and promotion as the main hurdles towards interdisciplinary research. A specific challenge in this context may arise from joint appointments that result in “double duty” and may not be rewarded as activities undertaken in one department may not be recognised in the other (NAS, 2004).

Additionally, success in academia is primarily based on peer review. Whether regarding publication in scientific journals, access to grants, promotion or university assessments like the REF, peer review helps to preserve disciplinary elites. Publications outside the core discipline may not be recognised by promotion or funding committees, sometimes simply because their contribution is not understood (NAS, 2004). In her interesting and rigorous study on the relationship between gender, specialisation, productivity and salary of a sample of sociologist and linguists, Leahey (2007) shows that higher levels of interdisciplinarity are associated with a lower number of publications. Lee (2007) further showed how disciplinary elites in economics in the UK were able to determine RAE quality criteria and in doing so skewed hiring decisions and research strategies towards mainstream economics and away from more interdisciplinary approaches. Martin and Whitley (2010) conclude from this that given the importance of publications for scientific advancement, these disciplinary elites decide what gets published and thus what type of research approach is to succeed. Indeed, Rafols et al. (2012) show that ‘excellence-based’ journal rankings, like the ones used in the REF, show a bias in favour of disciplinary research. They conclude that this would negatively affect the funding allocation for interdisciplinary research groups, leading to difficulties in establishing permanent interdisciplinary units within the university. Individual researchers, as a consequence, “face more constraints on the type of research they chose to pursue” (Martin and Whitley, 2010: 69) and in particular are deterred from pursuing interdisciplinary research (McNay, 2003).

While journal rankings and evaluations may be based in established disciplines, the relative scientific success of interdisciplinary projects may still be higher. Cummings and Kiesler (2005) show that a higher degree of interdisciplinarity in research teams reduces research outcomes if it involves researchers from more than one university, perhaps due to increased coordination costs. In a recent follow-up study that follows more than 500 research groups for a period of up to 9 years Cummings et al. (2013) find that larger teams are more productive than small teams, but that their marginal productivity decreases with disciplinary heterogeneity. They explain this with increased coordination and motivation efforts. Stvila et al. (2010) and Cummings and Kiesler (2007), on the other hand do not find such a trade-off. Mejer (2013) classifies these results further by finding that some overlap between the disciplinary backgrounds of team members is necessary for research to result in more research outcomes. She concludes that some members with an interdisciplinary background are needed in order to enable bridging across disciplines. Hollingsworth (2008) discusses the context of major discoveries and concludes that they are more likely to occur in an interdisciplinary environment. However, just like Mejer (2013) he argues that some cognitive overlap is necessary. He further stresses that not all research groups with low hierarchy and high diversity produce scientific breakthroughs, but that certain individual abilities to internalise new ideas are crucial.

We can conclude that interdisciplinary research may result in rewarding positions and more diverse and impactful research outcomes, however, due to existing disciplinary structures at universities and funding agents, hiring and promotion as well as publication in top disciplinary journals are more difficult to achieve for interdisciplinary faculty. This is primarily due to peer review mechanisms that, even in the case of interdisciplinary panels, evaluate research based on discipline-specific criteria (Mallard et al., 2009). It is therefore of importance for facilitators of interdisciplinary research, i.e. funding bodies and universities, to ensure that their processes do not favour unidisciplinary projects, that they acknowledge multiple leadership status on interdisciplinary projects, that they enable training in other fields, and that they employ a more flexible interpretation of funding and promotion guidelines (NSF, 2004).

5 INTERDISCIPLINARITY IN ENERGY RESEARCH

Energy security and climate change are topics of urgent policy concern and complexity and policy makers and researchers have called for an interdisciplinary approach to tackle pressing questions in energy research. Climate change requires the moderation of greenhouse gas emissions and recent developments have shown that policy instruments alone, e.g. regulation and tax, cannot bring the required transformation (Jaffe, 2012). Instead, technology development, government demand for new carbon-free or reduced technologies and the acceptance of new technologies needs to be accelerated. Research to tackle technological and societal questions regarding energy security in times of climate change require the combined efforts of interdisciplinary teams. Energy research is not a single disciplinary field but covers research regarding the production, conservation, transportation, use, management and policy of all forms of energy. Moreover, energy and environmental policy and politics affect the relationship between natural and social sciences as they "raise fundamental questions concerning the very distinction between the natural and the social" (Barry et al., 2008: 37).

In the UK, research councils have invested almost 700 million pounds into research relating to energy and climate change during the years 2008 to 2011 (Lyall and Fletcher, 2013). A new energy research centre (UKERC) was set up in 2004 to address energy controversies through interdisciplinary research. This chapter reviews some of the existing evidence on interdisciplinary energy research and its success.

5.1 CASE STUDIES ON INTERDISCIPLINARY ENERGY RESEARCH

In the UK, NESTA and UKERC have initiated several interdisciplinary energy initiatives in recent years. One is the Carbon Crucible programme, initiated by NESTA in 2009 and sponsored by UKERC, to run a series of workshops on the potential for climate change research (Blackwell et al., 2010). The goal of the programme was to foster interdisciplinary networks between participants. The evaluators of the programme noted that competition between participants and the short time scale initially limited communication, however, participants agreed to work on joint funding proposals (Blackwell et al., 2010). UKERC, as the result of these workshops, continues to build a community of energy researchers. Self-selection into the programme however leads to a bias towards researchers that are open towards interdisciplinary research paths (Blackwell et al., 2010).

Lyall et al. (2011) evaluated four interdisciplinary environmental research initiatives sponsored by the UK research councils. Two of these specifically address energy futures, the Tyndall Centre for Climate Change and the UKERC. Tyndall's research outcomes have influenced policy decisions and their recommendations directly led to the establishment of UKERC. They have also informed theory and generally increased the standard of interdisciplinary research. Both programmes have contributed to establishing a community of energy research. In analysing the working structure inside these centres, Lyall et al. (2011) found that Tyndall was firmly linked to external stakeholders and allowed these to shape the centre's research agenda. Tyndall then built interdisciplinary teams around specific projects each led by a theme head. At UKERC a push for policy relevance drove research themes, and interdisciplinarity was never directly encouraged but left to develop naturally. Most of their members identify as interdisciplinary and are thus open for collaboration. Lyall et al. (2011) also find that inside Tyndall many researchers migrate towards the social sciences during the programme duration as they gain an interest in policy, while social scientists themselves remain firmly anchored in their field and the least integrated. In some interviews, however, Lyall et al. (2011) find that research council criteria hampered some of the interdisciplinary endeavours at Tydall and that they "couldn't be as inclusive and as open as it was the original intention" (p. 36).

5.2 QUANTITATIVE STUDIES ON INTERDISCIPLINARY ENERGY RESEARCH

The first and to date only quantitative study to investigate interdisciplinarity in energy research that we are aware of is a study of publication and patent outcomes compiled in the Energy Science and Technology database between 1974 and 1990 (Tijssen, 1992). The measure of interdisciplinarity is based on the co-occurrence of subject classifications and shows that these are clustered around specific energy sources, with little to no connection between these. Social sciences play little to no role in most areas of energy research during the observation period and are acting separate from applied sciences and technology. Thus, while the area of energy research itself is interdisciplinary, specific research projects themselves were primarily held uni-disciplinary.

We can conclude that there is little existing research on interdisciplinary energy research initiatives. Existing studies show that while energy research as a subject area is highly interdisciplinary, not all researchers involved in the topic identify as interdisciplinary researchers. Boundary crossing primarily happens in engineering and natural sciences, while social sciences largely remain separate.

6 DISCUSSION

This document looked at some of the existing literature on interdisciplinary research and team science.

While there is a rich body of existing work, it still does not manage to pin down the best way to measure or evaluate interdisciplinary research. This means that while policy makers encourage research that crosses boundaries there are very few studies on the actual benefits of such projects. Most evidence is driven by the observation of successful research cases but mostly lacks a suitable comparison group to draw strong conclusions.

Researchers, evaluators and policy makers also do not agree on a definition for what constitutes interdisciplinarity which makes it difficult to measure and pin down the processes behind interdisciplinary research. Considering the field of energy research we only found a couple of empirical studies that look at interdisciplinary efforts. These showed that in a research area that is highly interdisciplinary, the research undertaken is not. Thus, a multilevel analysis is necessary that differs between:

- interdisciplinary research field
- interdisciplinary centre / institution
- interdisciplinary project
- interdisciplinary researcher

Within each level of analysis not all elements have to be interdisciplinary. For example, we may find disciplinary research streams inside an interdisciplinary field or centre. Similarly, an interdisciplinary research can still pursue disciplinary research lines. Such a multilevel analysis is currently missing in the literature.

The review further looked at the literature on research collaboration. Many of the arguments that arise in the discussion of interdisciplinary projects are rooted in the literature on collaborative teams. The classification suggested for interdisciplinary projects can largely be applied to collaborative projects and research fields that have a higher level of interdisciplinarity also show a higher level of collaboration. It is therefore important to distinguish between issues that arise as a result of team formation and those that arise as a result of cross-disciplinary work. Identifying those elements of interdisciplinary research that occur in all types of collaboration would help to pin down truly interdisciplinary benefits and concerns as well as help to address some of the issues relating to collaboration in general.

The review also looked at incentives and barriers to interdisciplinary research. It concluded that it is of importance for funding bodies and universities, to ensure that their evaluation mechanisms do not favour uni-disciplinary projects, that they acknowledge multiple leadership status on interdisciplinary projects, that they enable training in other fields, and that they employ a more flexible interpretation of funding and promotion guidelines. In addition is of importance for funding bodies and universities to consider the multiple levels at which interdisciplinary research can happen and design mechanism to foster it within and across all of these. This requires better and more flexible mechanisms to identify and foster interdisciplinary research.

Finally, throughout the review we stressed the importance of individual researchers as drivers of successful collaboration and interdisciplinarity. Individual level characteristics are crucial but can only develop and mature in the right research environment. Thus, the focus of policy is rightly on cultivating a research environment that embraces the interdisciplinary researcher.

REFERENCES

Audretsch, D. and P. Stephan, 1996, Company-Scientist Locational Links: The Case of Biotechnology, The American Economic Review 86, 641-652.

Barry, A., Born, G., Weszkalnys, G., 2008. Logics of interdisciplinarity, Economy and Society 37, 20–49.

Bammer G., 2008. Enhancing research collaborations: Three key management challenges'. Research Policy 37, 875-887.

Bammer G., 2012. Disciplining Interdisciplinarity: Integration and Implementation Sciences for Researching Complex Real-World Problems. Canberra, Australia: ANU Press.

Blackwell, A., Wilson, L., Street, A., Boulton, C. and Knell, J., 2009. Radical Innovation: Crossing Knowledge Boundaries with Interdisciplinary Teams. University of Cambridge Computer Laboratory. Technical Report UCAMCL-TR-760, Cambridge: University of Cambridge.

Blackwell, A., Wilson, L., Boulton, C. and Knell, J., 2010. Creating value across boundaries. Research report, London: NESTA.

Choi, B., and Pak, A., 2006. Multidiscplinarity, interdisciplinarity and transdisciplinarity in health research, services, education and policy: 1. Definition, objectives, and evidence of effectiveness. Clinical Investigative Medicine 29, 351-364.

Crane, D. and Small, H., 1992. American Sociology since the Seventies: The Emerging Identity Crisis. In: Halliday, T. and Janowitz, M. (eds.) Sociology and Its Publics: The Forms and Fates of Disciplinary Organization, 197-234. Chicago: The University of Chicago Press.

Cummings, J. and Kiesler, S., 2005. Collaborative research across disciplinary and organizational Boundaries. Social Studies of Science 35, 703-722.

Cummings, J. and Kiesler, S., 2007. Coordination costs and project outcomes in multi-university collaborations. Research Policy 36, 1620-1634

Cummings, J., Kiesler, S., Zadeh, R.B. and Balakrishnan, A., 2013. Group Heterogeneity Increases the Risks of Large Group Size. A Longitudinal Study of Productivity in Research Groups, Psychological Science 24, 880-890.

Ding, W.W., Levin, S.G., Stephan, P.E. and Winkler, A.E., 2010. The impact of information technology on scientists' productivity, Quality and Collaboration Patterns. Management Science 56, 1439-1461.

EC 2007. FP7 Taking European Research to the forefront. Brussels: European Commission Research Directorate-General.

ESRC, 2013, Impact, Innovation and Interdisciplinary Expectations. [Online]; Available: http://www.esrc.ac.uk/ funding-and-guidance/guidance/applicants/iii.aspx [22 June 2013].

Etzkowitz, H., and Leydesdorff, L., 2000. The dynamics of innovation: from National Systems and "Mode 2" to a Triple Helix of university–industry–government relations. Research Policy 29, 109–123.

Foray, D. and Gibbons, M., 1996. Discovery in the context of application. Technological Forecasting and Social Change 53, 263–277.

Gieryn, T., 1978. Problem Retention and Problem Change in Science. Sociological Inquiry 48, 96-115.

Heckhausen, H., 1972. Discipline and interdisciplinarity. In: Apostel, L., Berger, G., Briggs, A. and Michaud G. (eds.) Interdisciplinarity: problems of teaching and research in universities, 83–90. Paris: Organization for Economic Cooperation and Development.

HM Treasury, 2006. Science and innovation investment framework 2004-2014: next steps. London: HMSO.

Hollingsworth, J.R. and Hollingsworth, E.J., 2000. Major discoveries and biomedical research organizations: Perspectives on interdisciplinarity, nurturing leadership, and integrated structure and cultures. In: Weingart, P. and Stehr, N. (eds.) Practising Interdisciplinarity. Toronto: University of Toronto Press, 215-244.

Hollingsworth, J.R., 2008. Scientific discoveries: An institutionalist and path dependent perspective. In: Hannaway (ed) Biomedicine in the twentieth century. Amsterdam: IOS Press, 317-354.

Huutoniemi, K., Klein, J.T., Bruun, H. and Hukkinen, J., 2007. Analyzing interdisciplinarity: typology and indicators. Research Policy 39, 79-88.

Jaffee, A., 2012. Technology Policy and Climate Change. Climate Change Economics 3, 1250025 1-15.

Jones, B.F., 2009. The Burden of Knowledge and the "Death of the Renaissance Man": Is Innovation Getting Harder?, Review of Economic Studies 76, 283-317.

Jones BF, Wuchty S, and Uzzi B, 2008, Multi-university research teams: shifting impact, geography, and stratification in science. Science 322, 1259–1262.

Klein, J.T., 1990. Interdisciplinarity: History, theory and practice. Detroit: Wayne State University Press.

Klein, J.T., 2008. Evaluation of interdisciplinary and transdisciplinary research: a literature review. American Journal of Preventive Medicine 35, S116-S123

Klein, J.T., 2010. The taxonomy of interdisciplinarity. In: Frodeman, R., Klein, J.T., Mitcham, C. (Eds.), Oxford Handbook of Interdisciplinarity. Oxford: Oxford University Press.

Lakhani, K. R., Jeppensen, L. B., Lohse, P. A. and Panetta, J. A., 2007. The Value of Openness in Scientific Problem Solving. Working paper, Boston: Harvard Business School.

Larivière, V., and Gingras, Y., 2010. On the relationship between interdisciplinarity and scientific impact. Journal of the American Society for Information Science and Technology 61, 126-31.

Leahey, E., 2007. Not by Productivity Alone: How Visibility and Specialization Contribute to Academic Earnings. American Sociological Review 72, 533-56.

Lee, F.S., 2007. The Research Assessment Exercise, the State and the Dominance of Mainstream Economics in British Universities. Cambridge Journal of Economics 31, 309-25.

Lyall, C., and Fletcher, I., 2013. Experiments in interdisciplinary capacity-building: The successes and challenges of large-scale interdisciplinary investments. Science and Public Policy 40, 1-8.

Lyall C., Bruce A., and Marsden W., 2013. Identifying key success factors in the QUEST for interdisciplinary knowledge. QUEST project report, Edinburgh: University of Edinburgh.

Lyall C., Bruce A., Marsden W., and Meagher L., 2013. The role of funding agencies in creating interdisciplinary knowledge. Science and Public Policy 40, 62-71.

Mallard, G., Lamont, M., and Guetzkow, J., 2009. Fairness as Appropriateness: Negotiating Epistemological Differences in Peer Review. Science, Technology and Human Values 34, 573-606

Mansfield, E. and Lee, J.-Y., 1996. The modem university: contributor to industrial innovation and recipient of industrial R & D support, Research Policy 25, 1047-1058.

Martin B., and Whitley R., 2010. The UK Research Assessment Exercise. In: Whitley, R., Glaeser, J. and Engwall, L. (eds.), Reconfiguring Knowledge Production, Oxford: Oxford University Press, 51-80.

McNay, I., 2003. Assessing the Assessment: An Analysis of the UK Research Assessment Exercise, 2001, and its Outcomes, with Special Reference to Research in Education. Science and Public Policy 30, 47–54.

Mejer, M., 2013. The Impact of Knowledge Diversity on Inventive Performance at European Universities. GRASP Working Paper 41, Brussels: ULB.

Miller. R., 1982. Varieties of interdisciplinary approaches in the social sciences. Issues in Integrative Studies 1, 1–37.

Mulkay, M., 1974. Conceptual Displacement and Migration in Science: A Prefatory Paper. Science Studies 4, 205-234.

National Science Foundation (NSF), 2006. Investing in America's Future Strategic Plan FY 2006–2011. Washington, DC: National Science Foundation.

Pantin, C.F.A., 1968. The relations between the sciences. Cambridge, UK: Cambridge University Press.

Porter, A. L. and Rafols, I., 2009. Is science becoming more interdisciplinary? Measuring and mapping six research fields over time. Scientometrics 81, 719–745.

Rafols, I. and Meyer, M. 2010. Diversity measures and network centralities as indicators of interdisciplinarity: Case studies in bionanoscience. Scientometrics 82, 263–287.

Rafols, I., Leydesdorff, L., O'Hare, A., Nightingale, P. and Stirling, A., 2012. How journal rankings can suppress interdisciplinarity. The case of innovation studies and business and management. Research Policy 42, 1262-1282.

RCUK 2006. RCUK Response to the Government's Science and Innovation Investment Framework 2004-2014 Next Steps Consultation. London: Research Councils UK.

Rhoten, D. and Parker, A., 2004, Risks and Rewards of an Interdisciplinary Research Path. Science 306, 2046.

Rhoten, D. and Pfirman, S. 2006. Women in interdisciplinary science: exploring preferences and consequences. Research Policy 36, 56-75.

Rinia, E., van Leeuwen, T., Bruins, E., van Vuren, H. and van Raan, A., 2002. Measuring knowledge transfer between fields of science. Scientometrics 54, 347-362.

Rosenfield, P. 1992. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Social Science of Medicine 35, 1343–1357.

Stirling, A., 2007. A general framework for analysing diversity in science, technology and society. Journal of the Royal Society Interface 22, 707-719.

Stokols D, Hall KL, Taylor BK, and Moser RP., 2008. The science of team science: overview of the field and introduction to the supplement. American Journal of Preventive Medicine 35, S77-S89.

Stvilia, B., C. Hinnant, and K. Schindler, 2010. Composition of scientific teams and publication productivity at a national science lab. Journal of the American Society for Information Science and Technology 62, 270-283.

Subramanyam, K., 1983. Bibliometric studies of research collaboration: A review. Journal of Information Science 6, 33-38.

Sung, N.S., Gordon, J.I., Rose, G.D. et al., 2003. Educating Future Scientists. Science 301, 1485.

Tijssen, R., 1992. A quantitative assessment of interdisciplinary structures in science and technology: Co-classification analysis of energy research. Research Policy 21, 27-44.

Tress, B., Tress, G. and Fry, G., 2006. Defining concepts and the process of knowledge production in integrative research. In: Tress, B., Tress, G., Fry, G.,Opdam,P. (Eds.), From Landscape Research to Landscape Planning, The Netherlands: Springer, 13–26.

Wagner, C.S., Roessner, J.D., Bobb, K., Klein, J.T, Boyack, K.W., Keyton, J., Rafols, I. and Borner, K., 2011. Approaches to understanding and measuring interdisciplinary scientific research IDR: A review of the literature. Journal of Informetrics 165, 14-26.

Weingart, P., 1997. From "Finalization" to "Mode 2": Old wine in new bottles? Social Science Information 36, 591–613.

Whitfield, J., 2008. An indifference to boundaries. Nature 451, 872-873.

Wuchty S, Jones BF, and Uzzi B. 2007. The increasing dominance of teams in production of knowledge. Science 316, 1036–1039.

Yegros, A., D'Este, P. and Rafols, I., 2013. Does interdisciplinary research lead to higher citation impact? The different effect of proximal and distal interdisciplinarity. DRUID Conference Paper, Copenhagen: DRUID.

Zuckerman, H., 1967. Nobel Laureates in Science: Patterns of Productivity, Collaboration, and Authorship. American Sociological Review 67, 391-403.

