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Are the impacts of wind energy reversible? Critically reviewing the research literature, the governance challenges and presenting an agenda for social science

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Abstract

The extent to which the impacts of renewable energy development might be reversible is an important dimension of debates about environmental acceptability, magnified in significance by the sector's rapid expansion and the inexorable ageing of facilities. However, despite frequent claims that the impacts of renewable energy are reversible, the complex realities of impact (ir)reversibility have attracted minimal systematic research. This paper addresses this gap with the first review of the research literature on impact (ir)reversibility, focused on onshore wind, and makes a number of contributions. Firstly it shows that determining whether impacts are reversible or not inevitably entails selective, value-laden judgements about what matters and why. Secondly, a problem with much of the existing literature on (ir)reversibility issues is its abstract and hypothetical nature, detached from actual end-of-life decisions about renewable energy facilities, and their relationship with sites and landscapes. These insights are used to generate a conceptual framework for investigating impact (ir)reversibility - emphasising the benchmark, value basis, object of focus, allocation of responsibility, and regulatory mechanisms - and the ways that long-term, end-of-life impacts are governed. The value of this framework is demonstrated through three empirical vignettes from the UK, and used to generate an agenda for future research.

Key words:
Renewable energy, onshore wind, irreversibility, reversibility, decommissioning, environmental impacts

1.0 Introduction

Avoiding irreversible environmental damage is a prominent principle of sustainable development [1,2], with important implications for energy. Indeed, energy systems provide some of the most widely-referenced instances of the potential for present-day decisions to have long-term, irreversible impacts on future generations. The considerable time frame across which radioactive waste from nuclear power remains hazardous is a prime example [3–5]. So too is fossil energy: historically, in relation to resource depletion but today, mostly for its contribution to such climatic perturbation that ‘planetary tipping points’ [6] might irretrievably be passed. Concern for the long-term environmental effects of energy choices is an important driver for investigating more sustainable energy systems.

By comparison, relatively little research attention has been given to issues of impact (ir)reversibility in relation to renewable energy – a reflection, perhaps, that renewables largely obviate the totemic long-term impacts of fossil or nuclear systems. Certainly, large-scale hydro has attracted concerns about permanent, large-scale effects, such as the displacement of peoples from impounded water bodies [7]. However, until recently there has been little attention to end-of-life issues with key renewable energy technologies, like onshore wind or solar power [8–10].

This research deficit is increasingly problematic, for a number of reasons. With an installed capacity of 594, 253 MW onshore wind and 578 553 MW Solar Photovoltaic worldwide [11,p.16] and rapid growth still underway, so the potential scale of legacy issues increases. In temporal terms, as extant facilities inexorably age, so the issue of ‘what next’ – repowering, decommissioning, or abandonment [12, 15]? – makes whether the effects of such developments can be ‘reversed’ an increasingly pressing question [8,13,14].

Moreover, whether the effects of renewable energy technologies are reversible is not simply a looming future concern. Competing claims about (ir)reversibility are widely deployed right now to influence how far, and where, renewable energy should expand, in the context of growing competition for land. One can find both academic researchers and developers asserting that a relative advantage of renewable energy systems, such as onshore wind, is that its impacts are reversible, because at the end of its life the infrastructure can easily be removed, leaving limited or minimal impact on the site [15–20]. Equally, one can find renewable energy critics representing renewable energy as having enduring impacts, causing a ‘loss’ of land to other uses [for example,21]. Whether impacts are reversible is evidently a claim that can ameliorate or intensify impact concerns, begging questions about how policy-makers do or should respond. However, the concepts of ‘reversibility’ and ‘irreversibility’ have entered the lexicon of debate about the merits of different energy pathways without being clearly conceptualised [22], unpacked or examined empirically.

In this review paper, we respond to these issues by critically examining the question of whether the impacts of renewable energy – and onshore wind in particular – can be considered to be reversible. By way of working definition, we interpret reversibility to mean the ability to remediate material impacts or changes that have occurred as a result of developing renewable energy capacity, and thus avoid leaving harmful legacies for the future. Our first contribution is to provide the first significant review of existing research that bears upon this question, with particular attention to analyses from the social sciences. Given the scale of impending end of life issues, and the circulation of untested claims about impact (ir)reversibility, we see a pressing need to gauge the extent of existing knowledge and understanding. As our analysis will show, investigating this subject necessarily requires engagement with the ambiguities of the concept of (ir)reversibility [22,23] and – in methodological terms – required a review approach that can respond to the nascent and disparate treatment of impact (ir)reversibility in current research. Drawing on the findings of this review, we propose a conceptual framework for understanding and investigating impact (ir)reversibility, with relevance to the ways that long-term, end-of-life impacts are governed. This is our second contribution. We demonstrate the value of this conceptual framework by using it to interrogate three empirical vignettes from onshore wind development in the UK, each representing a different set of end-of-life governance challenges.

The paper is structured as follows. Section 2 provides the methodology for our literature review and empirical vignettes. In Section 3 we give the findings from our review, the main areas of research activity and the gaps, and draw out the wider implications. A key point is that claims that the impacts of renewable energy are reversible or irreversible are ineluctably entangled with wider ontological and value positions, and thus invariably partial and selective in what they emphasise. From this, in Section 4, we develop our conceptual framework, focusing on the key choices from which claims about impact (ir)reversibility are constructed. In Section 5 we apply this framework to the three empirical vignettes, examining: (i) policy choices over which effects of wind farm development to treat as reversible or irreversible; (ii) the prospects of conflict over impact reversal in end-of-life decisions; and (iii) decommissioning, and the selectiveness such practices entail. The final section presents the main conclusions and a future research agenda.

2.0 Methodology

2.1 Approach to the literature review

In seeking to capture and make sense of the state of existing research on impact (ir)reversibility and renewable energy, our approach combined elements of systematic review with those of narrative literature review [24].

For the systematic element, the search focused on research articles in peer-reviewed journals, published in English. A wide time-frame was adopted, including all articles published up until the end of December 2020, and included articles with the key search terms mentioned in titles, key words and abstracts. The search had two strands. The first involved searching the Scopus and Web of Science databases using the search terms ‘energy’ and ‘renewable energy’ coupled with ‘irreversibility’ and ‘reversibility’. This revealed very few articles that explicitly linked renewable energy with (ir)reversibility. For the second strand of the search we tightened the source focus to the major peer-reviewed journals in the field of energy social science, including *Energy Policy*, *Energy Research and Social Science, Renewable and Sustainable Energy Reviews* and *Applied Energy*. However, we expanded the search terms from ‘irreversibility’ and ‘reversibility’ to also embrace relevant end-of-life practices – ‘restoration’, ‘abandonment’ and ‘decommissioning’ – where impact (ir)reversibility might be an issue.

The scope of the treatment of(ir)reversibility in this paper focuses on the environmental and social *impacts* that renewable energy development creates. This in turn set the criteria for including and excluding articles from our searches. Articles that discussed ‘(ir)reversibility’ in ways irrelevant to environmental impacts were excluded: i.e. articles where irreversibility refers to the optimal timing and opportunity costs of choices in investment appraisal, as reviewed in [23,25], or thermodynamic properties of energy conversion processes. Beyond this, articles were excluded where the attention given to irreversibility, reversibility, end-of-life practices, or to energy was just too small, too lacking in data, to provide anything meaningful to review. To provide transparency to our approach, the set of articles yielded by the search and used in the analysis are given in Table 1 [26]. In practice, most focused on wind energy, though we included analyses of other renewable energy technologies as they offered relevant insights to the wider state of knowledge.

As the findings will show, impact (ir)reversibility in relation to renewable energy is a somewhat fugitive subject, covered in a sparse and patchy way across disparate literatures – qualities that make it difficult to capture through systematic review [24]. For this reason, the systematic element was supplemented by using narrative literature review, drawing in a wider set of relevant materials known to the authors. This is an inevitably subjective process but it conferred a number of advantages. It helped to supplement the narrowness of the systematic review results by incorporating wider perspectives on (ir)reversibility and making links to related debates, all of which befit this multi-dimensional problem. The narrative analysis approach also helped significantly in making sense of the state of existing knowledge, and to interpret the key implications.

Category (of main subject matter)	**Number of items identified**	**Items selected for inclusion**
Irreversibility concepts	4	22, 23, 29, 31
Life-cycle analysis and cognate techniques	16	33, 34, 35, 36-42, 44, 45, 46, 47, 55, 57
Recycling/circular economy	4	48, 50, 52, 53
Total environmental impacts/ externality studies	3	19, 43, 56
Landscape impacts	3	17, 20, 66
Ecological restoration	2	64, 65
Offshore wind decommissioning	6	70, 72-76
Life extension and decommissioning (onshore renewables)	8	8, 9, 12, 49, 54, 85, 105, 109
End of life issues and publics	5	16, 86, 93, 94, 98
End of life issues and developers	2	18, 95
TOTAL	**53**	

Table 1: Results from the systematic review

2.2 Vignettes

The value of the conceptual framework for analysing impact (ir)reversibility was tested through a series of empirical vignettes. The data for these was drawn from research conducted from 2016-2019 in the UK, to examine how end-of-life decisions for onshore wind were being handled. The research methods involved textual analysis of renewable energy and planning policies, at national (England, Scotland, Wales) and local level (43 documents in total); and 24 in-depth interviews with developers, local authority planners, communities and government policy makers engaged in regulatory design and project consenting. The research was structured to focus on issues of policy design and change in general, but also to elucidate the (ir)reversibility issues emerging with a number of onshore wind farm case studies, for which further analysis of the planning applications, the consultation responses and ultimate decisions was conducted. Across the research, both textual data and interview transcripts were subjected to thematic coding.

3.0 Interpreting irreversibility in the context of renewable energy

3.1 Introducing 'irreversibility'

It is a widely stated argument that delivering sustainable development requires careful attention to the avoidance of adverse, irreversible impacts[1], particularly because such outcomes can cause injustice to future generations. Although there has been extensive debate about the extent of our obligations to posterity (e.g. [27]), many formulations contend that actions that risk denying future generations the opportunities to enjoy at least an equivalent quality of life to the present are unjust [4], hence decisions that might deprive future generations of important assets, or encumber them with major risks, are problematic.

Most analytical interpretation of the irreversibility concept that is relevant to our concerns with development impacts, has unfolded within economics, at the interface between neo-classical welfare perspectives and strands of environmental economics [23, 28,29]. Environmental economists such as Pearce and Turner [28] have questioned the appropriateness of dealing with future environmental costs and benefits by converting them into monetary values and discounting them in the name of allocative efficiency, as this ignores the way that certain environmental features are important, non-substitutable and non-restorable in their implications for human welfare, and thus can be irreversibly lost. Classic examples are biodiversity, a stable atmospheric system, clean water, and valued, unspoilt landscapes [30]. Importantly, damage to each could be irreversible in different ways [31]: being either a de facto permanent loss (species extinction), incapable of deliberate reversal by humans on a relevant timescale (climate change), or a matter of meaning and value (as with the wild and natural qualities of certain landscapes).

A few points emerge immediately from this introductory discussion. Firstly, even within economics 'not much work has been done to clarify the concept of ... irreversibility' [22, p8]. Second, the salience of concerns for irreversibility is bound up with the issue of importance i.e. we should be concerned about the irreversible loss of or damage to things that matter, not things that are trivial [23]. Thirdly, that whether impacts are meaningfully reversible is not just a matter of human ingenuity and effort but relates to what it is in the environment that we value and why. The relevance of these points becomes clear when we turn to explore those clusters of research that have engaged with (ir)reversibility-related issues in relation to renewable energy.

3.2 ‘The impacts of renewable energy are potentially reversible’

The main clusters of research identified by the review, that engage with long-term impact questions for renewable energy, focus on two sets of environmental management practices. The first focuses on analysing the ‘total lifetime impacts’ of renewable energy infrastructure, often adopting some form of life-cycle analysis (LCA). Such studies use LCA and techniques like ‘environmental adders’ or ‘energy payback times’ to assess the impacts of renewable energy, often for some comparative purpose [32–36]. LCA studies have also shown the environmental benefits of repowering older, low-powered turbines with newer, higher-powered turbines [37,38]. Nugent and Sovacool [39] use their meta-survey of analyses of the ‘lifecycle greenhouse gas emissions’ of wind and solar energy systems, to show the relative merits of different configurations. A common conclusion of the cross-technology LCA studies is that wind and solar energy have lower lifetime environmental footprints than nuclear or fossil-fuel systems, mainly because they lack the impacts (and thus reversibility questions) associated with fuel production, processing, combustion and transport [40,41], or disposal of waste products [42]. Nevertheless, LCA-type analyses also show that renewable energy is not impact free [43,44], and that many impacts arise in fabricating the equipment, raising questions about impacts – some potentially irreversible – at sites of materials production.

However, although LCA has the caché of comprehensiveness, relatively few studies embrace all stages of the lifecycle, with the decommissioning stage of renewable energy infrastructure being especially poorly covered [39,45,46]. Of the studies that do embrace decommissioning, the potential recapturing of material value by recycling is identified by some as reducing total lifetime impacts [36,39].

The treatment of renewable energy infrastructure at the end of its life is the focus of the second cluster of research identified, which examines the prospect of creating closed-loop, circular economies [47] that can ‘reverse’ the downstream effects of these technologies through the productive re-use of redundant machinery [48]. Sica et al [47] have noted how extending circular economy principles to ‘upstream’ manufacturing and ‘downstream’ end-of-life recovery can potentially reduce energy consumption, resource intakes (some of them hazardous substances), wastes and associated pollution risks. A further motivation for applying circular economy thinking is to avert resource depletion irreversibilities for the rarer materials entailed in manufacturing renewable energy infrastructure [49].

Creating more circular economies does not reduce impacts entirely, creating some legacy effects. This is a reflection of entropy, but also the inevitably imperfect process of commodification – that the transformation of materials into waste and resources itself always has energy and transport effects and its own wastes and pollution. It is also a consequence of material complexity, notably the composite materials that make turbine blades and other components difficult to recycle [50–53], requiring upstream action to ‘plan for decommissioning’ [14, p.4].

These bodies of impact management research present an important qualification to casual assertions of ‘potential recyclability’ or ‘impact reversibility’ regularly attached to wind and solar power. Nevertheless this research also exhibits qualities which mean that it talks past some key facets of (ir)reversibility debates. There is a tendency to reductionism in these studies, especially in LCA, because the desire to aggregate different impacts for comparative purposes, means that impacts are expressed in particular functional units [39] such as CO_2-equivalent emissions per kilowatt hour, or energy and resource flows. This tends to hide whether *particular* impacts are likely to have difficult-to-repair consequences, and side-lines unquantifiable impacts (see also [43]). Such reductionism can also be problematic given that, as Sunstein [23] argues, a quality of irreversible impacts is that goods with non-substitutable, non-fungible qualities are particularly likely to be at stake.

Many of the studies, especially for circular economy development, still talk mainly in generalised and hypothetical terms about the potential for such downstream, end-of-life reclamation, recycling and re-use. Empirical studies of what actually happens to most redundant renewable energy facilities and equipment are scant [54]. LCA studies that have engaged with end-of-life issues tend either to defer to arguments that the majority of components are (potentially) recyclable [e.g. 39] or treat (actual) decommissioning as largely unpredictable [45,55].

A third issue, shared by both LCA and circular economy research is a tendency for abstraction. To a large extent these studies treat renewable energy systems like products, or placeless material inventories, somewhat abstracted from time and space, not as elements of facilities that are spatially- and socially- embedded within particular sites and landscapes. The problem here may be that impacts on land are not readily reducible to the kinds of metrics used in such studies (material flows, energy, carbon). While studies often acknowledge the landscape impacts of renewable energy, some embracing the importance of reversibility as a measure of impact [56], they largely ignore the intensity of the land use impact and its wider social and environmental effects [57]. Such literature tends therefore to ignore how renewable energy technology such as wind turbines and associated equipment gets entangled with a site, its human and non-human inhabitants, creating a diverse ecology of changes to landscape and natural processes. Not all of these effects may ‘reverse’, even if individual facility components can – in theory – be removed and recycled.

This neglect of land use dimensions matters because the effects on landscape and places are widely recognised as dominant societal concerns about renewable energy expansion, especially for onshore wind [58], and have important temporal dimensions [20]. And as we noted in the introduction, competing claims about the reversibility of the impacts of renewable energy development are very much directed to the nexus between infrastructure, sites and project consenting.

To date, then, the two main bodies of research that have engaged with long-term impact issues have only patchily considered whether the impacts of onshore wind energy can be reversed. There is much assumption that they can be; and some analysis of how the material components might be recycled (incompletely, in all probability). However, both perspectives are disembedded somewhat from the concrete situations in which prospective infrastructure removal takes place. Confronting these often abstract, reductionist claims are literatures from the social and natural sciences, which question at a fundamental level, the prospect of changes being ‘reversed’.

3.3 ‘Change is always irreversible’, and may be desirable

Challenges to the very notion of reversibility come from literatures that engage more directly with the temporality of the physical world and social life.

In a series of important analyses, Barbara Adam argues that time has multiple dimensions, simultaneously present and inter-connected [59–61]. The notion of reversibility, however – that time is bi-directional – is, she argues, only meaningful in the abstract, idealised conditions of Newtonian physics, or within the human constructs of measurable 'clock time'[62]. Beyond these very particular conditions, time is constituted by intertwining and material aspects that are ineluctably irreversible - processes of decay and ageing, applicable to people but also machinery (like wind turbines); and ecological processes. When discussing machines she argues that 'they are not abstractable from their environment' as 'their development and use have consequences that become integrated into the complex web of ecological interconnections which in turn impact on social life' [61, p.167]. Consequently, Adam argues that time flows in one direction: 'there is an unalterable temporal direction in things, organisms, events and human knowledge. There can be no un-being or un-becoming' [63, p.40]. From this perspective all actions and decisions are irreversible, including non-decisions, and they all irrevocably affect the inheritance of future generations (see also discussion in Manson [22]).

To date, such insights have been little considered by renewable energy researchers. Nevertheless, there are two main areas in which the uni-directionality of time's arrow bears on debates about impact (ir)reversibility for renewable energy projects.

The first concerns site restoration – i.e. when a renewable energy facility reaches the end of its working life, can the land it occupies and the wider impacts be returned to the status quo ex ante? This issue has been given some attention by hydro-power researchers, in the context of the dam removal agenda [64]. The review identified no systematic research into how such issues play out with onshore wind. The minimal literature that exists has dwelt mainly on the restorability of impacts on habitats and species ([65,66], see review in Zerrahn [43]). Researchers have begun tracing the emergence of potentially innovative restoration strategies, relying on off-setting: Kling et al [67], for example, note that areas of the US have begun to consider an offsite, regional approach to mitigation in order to sustain functional ecosystems rather than recovering aspects in a piecemeal approach. Impact reversibility has also been used (hypothetically) by landscape analysts to gauge the resilience of traditional landscapes to potential changes, including wind farms ([17]; see also [20]).

More generally, researchers looking at onshore wind and solar power have often considered site restoration to be straightforward- which it may be, compared to the effects of hydrocarbon exploitation and nuclear energy. However, beyond renewable energy research, there is a considerable literature spanning ecology and philosophy showing that issues of restorability are complex, uncertain and combine technical and value-based concerns [68]. The prospects of full restoration may founder on concerns about the technical challenges of minutely replacing particular pre-existing ecosystems. However, where intrinsic value is placed in a specific landscape or ecosystem, derived from the particular natural and social processes of its creation, then many environmental philosophers would argue that full restoration by human hands is logically impossible, no matter what technical skills we may be able to deploy [69]. This is an illustration, after Manson [22], of how the specificity and content of 'state description' can affect the classification of damage as irreversible.

Restoration issues are more actively debated in the realm of offshore wind energy, where there is a body of extant research on decommissioning, driven by international conventions [70–72]. Debate centres particularly on the potential merits of allowing some sub-surface elements of turbines to remain in situ, post-decommissioning, to exploit the tendency of such features to aid habitat diversity and biodiversity [73–75], rather than mandate complete removal. Values and benchmarks are at the centre of these debates, and include visual amenity and navigation (favouring removal of above- and near-surface elements), metrics of species and habitat change, and consideration of the risks that may arise from complete removal (e.g. of cables and scour protection)[76].

The second area in which the uni-directionality of time bears upon the dynamics of renewable energy development concerns the processes by which energy development intertwine with other elements of places to exercise enduring effects, which go beyond land and site-based impacts. Analysts have identified how the development of particular energy sectors can create supportive conditions – technically, economically and socially – for future development. The concentration of nuclear facilities in existing 'nuclear oases' is a famous example [77]. In effect, we can observe path dependencies in energy development, with the new facilities building on past conditions but also recasting the direction of future development. This has relevance to renewable energy like onshore wind, too. The sense that renewable energy can send landscapes and the livelihoods associated with them in new and, for some, inappropriate development paths has been widely observed in public responses, expressing concerns that renewable energy infrastructure risks 'industrialising' previously 'rural' areas [15,78–80]. Such public concerns appear well founded, given the path-dependent tendencies for wind farm sites to be more readily consented for repowering compared to 'greenfield' sites [81], perpetuating 'landscapes of power' [15].

Of course, impact reversal is not always what is sought. Although debates about reversibility are usually attached to infrastructure *removal* and the treatment of remaining impacts, this is just a subset of the situations in which (ir)reversibility becomes relevant, and not necessarily the most prominent. Indeed, there are strong incentives to maintain the presence of renewable energy facilities. Doing so sustains the output of low carbon energy, as well as the other commonly-cited benefits associated with wind energy such as employment and financial benefits for the local community [82,83] and, in some locations, contributes positively to place identity [84]. Increasing facility and component life expectancy also lowers lifetime greenhouse gas emissions from the facilities [39]. As Wachs and Engel argue [46, p.9], 'renewables are attractive in part because the same plot of land can be used indefinitely'.

However, keeping renewable energy in place is itself a more complex accomplishment than is generally recognised [8]. Firstly the facility can be maintained over time through extending the consent period of operation and replacing any worn out components: sometimes like-for-like; sometimes with more radical reconfiguring [9]. Secondly, a site can be repowered involving removal of existing infrastructure and replacement with new infrastructure often of an increased capacity. In the case of wind energy this usually involves fewer larger turbines than before, in a different layout [85], thereby raising additional questions regarding reversing the effects of older turbines as well as the new. With both equipment replacement and repowering, we see how 'long-term stability is invariably based on short-term impermanence and uncertainty' [59, p.130]. Ultimately, infrastructure that is no longer operational can be removed from a site through decommissioning. Given these possibilities we see further complexities of applying concerns for (ir)reversibility in real life settings: in this case, that questions about whether and how far impacts should be reversed may not apply simply to a clear, singular end-point but emerge episodically over time.

3.4 Public and stakeholder attitudes to renewable energy (ir)reversibility

Our literature review also revealed some surprising gaps in knowledge. Given the voluminous research on public and stakeholder attitudes to renewable energy in general, and onshore wind in particular, it is remarkable that we identified no research that interrogated what different social actors felt about the prospects of impact (ir)reversibility, and little on actor preferences and agendas for end-of-life decisions in general. One is often left seeking insights from cognate studies.

There is research suggesting that extending the life of an existing wind farm, or repowering, is generally less likely to generate public conflict than new projects on new sites [86,87]. Attitudes to wind power developments have also been suggested to follow a U-shaped curve pattern of local public acceptance, ranging from very positive when people are asked about wind energy in general, to less positive when people experience an application in their local area, to more positive again following construction of the development. This phenomenon is attributed to initial fears not being realised, impacts being less than expected, and wider familiarisation [88–90]. However, little research actually examines public feelings about the prospective 'reversal' of renewable energy as facilities approach the end of their initial life.

Temporal processes are bound into the formation of valued landscapes, the impact on which is widely identified as critical in shaping public responses to energy infrastructure, particularly wind farms [91]. Temporality is also an important component of explanatory constructs for public attitudes, like 'place attachment' [92], including variations in place relations across people's life course [93]. Although a major focus of this research is understanding public preferences for continuity, most social science research focuses on the dynamics of attaining project consent and those initial, prospective environmental changes, not long-term outcomes. Of the handful of exceptions, Frantál's [86] analysis of 'post-operational' experiences of wind farms in the Czech Republic find 'easy recycling of the facility' to be a minor factor affecting project acceptance. That wind turbines constitute 'a transient intrusion into the landscape that can easily be removed' [94, p.209], in contrast to coal or nuclear, has been identified as an element of pro-wind discursive frames in Germany. The prospects of actual removal, and what that might entail, is little considered.

Another limitation of the existing literature on renewable energy and impact (ir)reversibility, is its tendency towards idealism, exemplified in numerous efforts to delineate what would constitute best practice. These tend to assume that decision-makers in private and public sectors will act in accordance with the principle of avoiding serious irreversible impacts and not discount the future. However, surveys have shown plant operators affording low priority to the scope for infrastructural removal and intergenerational justice [95, p.8]. Governments responsible for potential regulation may also be similarly short-termist in orientation [96], unwilling to impose long-term burdens on an industry they regard as desirable now. Research in the US identified that permitting often only regulates readily measurable environmental and sensory impacts rather than impacts that are related to the creation of public goods such as biodiversity or quality of life [97]. Moreover, inoperative wind turbines are clearly not immune to abandonment and falling into dereliction [12,54,98], like other renewable energy facilities e.g. hydropower facilities [99] – casting effects into the future after production has ceased. This matters, because early attitudinal research also shows inoperative turbines to foster negative public attitudes to the wind energy sector [98].

4.0 (Ir)reversibility in action – a conceptual framework

One immediate conclusion from the literature review above is that there is not yet much published research that addresses whether the impacts of renewable energy development might be considered reversible. Very few articles indeed talk explicitly about impact (ir)reversibility and renewable energy. A larger set of articles address end-of-life issues that relate to questions of impact reversibility – especially decommissioning, to a lesser extent restoration – but, within these texts, (ir)reversibility is often an implicit, elusive concern, rarely subject to close scrutiny. Such results are perhaps unsurprising for a nascent problem still 'in the making'.

Despite these limitations, one can draw out a number of relevant points for interpreting claims and assumptions about the potential (ir)reversibility of renewable energy developments.

Firstly, claims about whether impacts are reversible are fundamentally caught up with wider ontological positions about the nature of the world [22] and beliefs about value i.e. what is valuable and why. For the body of literature concerned with impact measurement and materials recycling, renewable energy technologies are often reduced to component materials, detached from time and space, such that the impacts of can be presented as, potentially at least, having few long-lasting effects. Other perspectives would treat renewable energy technologies and facilities as ineluctably enmeshed in social and ecological processes in concrete situations, triggering an array of consequences, which are fundamentally incapable of reversal. From this perspective, irreversibility is ubiquitous and omnipresent. Different bodies of literature tend therefore to adopt perspectives that privilege a certain understanding of what constitutes relevant impacts and effects. This gives 'avoiding irreversible impacts' the qualities of an essentially contested concept [100], where broad normative support nevertheless belies complexity and debate over the appropriate analytical underpinnings and response.

Following from this, the second point is that claims that the impacts of wind energy development are reversible or irreversible are inevitably selective and partial. This can be illustrated by debates about whether renewable energy facilities and their sites can be fully restored once production has ceased. This is an issue which depends on what values and benchmarks are prioritised and in what detail they are specified [101]. Different positions may emphasise particular aspects of the technology, the facility, wider socio-ecological relations or societal expectations. For onshore wind, for example, it is easy to imagine how different benchmarks for judging impacts to be adequately 'reversed' could be mobilised - agricultural productivity of the land occupied (with its systems of grading); metrics of habitat and species diversity; or a sense of 'wildness' etc – each selective and partial, and each generating different answers and challenges for the prospects of impact reversibility. Depending on the position adopted, what counts as adequate impact reversal may not mean 'the most comprehensive replica'[102, p.7] of the status quo ex ante.

Our third deduction from the literature review, is that a large proportion of the reflections on – and engagement with – issues surrounding (ir)reversibility come from the perspective of the 'detached analyst', whether it is researchers concerned with better impact management, philosophers or critical sociologists. Many offer normative prescriptions for policy and practice, yet most are at some remove from the dynamics of actual decisions affecting the long-term consequences of renewable energy infrastructure.

What is particularly absent from the existing literature is contributions from the social sciences, investigating the factors shaping actual end-of-life decisions and outcomes [8,86]. The relative absence of the social sciences is problematic, precisely because whether effects are (ir)reversible is not a simple, technical question, but simultaneously a matter of ontological and value perspective, raising classic social science questions about whose (analytical or political) perspective dominates, which perspectives are institutionalised in governance arrangements, and with what consequences.

What is needed, we argue, is further effort to understand how claims about irreversibility get mobilised in the field, and with what effects. This does not imply a relativist position on the meaning of 'irreversibility'. How it is interpreted can have profound material consequences for the impact legacy of renewable energy development; in effect, it shapes what future generations inherit. What is required, therefore, are tools that enable us to identify and render visible the different interpretations of (ir)reversibility and their consequences.

To assist investigations of the treatment of (ir)reversibility in practice, we draw from the literature review to propose the following conceptual framework, which provides a working definition of the concept and a distillation of the key dimensions of impact (ir)reversibility likely to be at stake. The framework is summarised in Table 2.

Working definition *Reversibility in the case of renewable energy infrastructure concerns the ability to remediate material impacts or changes that have occurred as a result of developing renewable energy capacity, and thus avoid leaving harmful legacies for the future*	
Key questions	**Component issues**
On what basis is the judgement of impact (ir)reversibility to be made?	What is used as a benchmark? (the status quo ex ante, or has the presence of a renewable energy facility been accepted as changing the visual or ecological baseline?) What is valued here, about the facility, the environment or social relations, and should be taken into account? How is it valued? What is being assumed about the future use of the site, and potential path-dependent effects?
To what entities should concerns about (ir)reversibility apply?	To constituent materials and components of the renewable energy infrastructure (and which ones)? To aspects of the site where the facility is developed? To wider relations between technology, site, places and publics? What is included and what is omitted from such concerns?
On whom does the responsibility to address end of life impact fall?	The developer, owner or operator of the facility? The land owner? Public institutions and public money? For how long a time-period do any responsibilities apply?
How are long-term impacts regulated?	What is the balance between voluntaristic/market measures and mandatory regulations?

	How are benchmarks, objects of regulation, the allocation of responsibility, and time period, inscribed into regulatory measures? To what extent are particular outcomes secured?
What scale of long-term effects matter?	Are some irreversible effects too trivial to consider? Can the costs of pushing for fuller reversal of impacts be outweighed by the benefits of retaining some of the changes?

Table 2: Investigating impact reversibility – a conceptual framework

Researchers from numerous disciplines have much to offer to elucidate the issues in table 2, but social scientists can make a particular contribution, given core concerns with agency, power and governance. It is important to understand which actors articulate certain conceptions of (ir)reversibility, and which gain greatest traction (in policy and regulatory practice) and why. There are clearly potential distributive consequences to the choices made: some interests and agendas will be advanced and others marginalised. Social science insights may also be valuable because responses to the key questions in Table 2 are very likely to be contested. Taking steps to reverse impacts can have costs: hence for all that wind farm developers may wish to maintain their image as environmentally conscious [50], the industry may still wish to contain the temporal, spatial and substantive scope of responsibility for the impacts that their facilities create. Equally, opponents of renewable energy development may recognise that claims about irreversibility 'operates as a kind of amplifier' of impact concerns [23, p.235] that can advance their goals.

To demonstrate the value of this framework, we present three empirical vignettes from the UK. Each is designed to illustrate our arguments about the selectivity of claims making and institutional design about impact (ir)reversibility and to indicate the implications of the choices that are being made (or side-stepped). Each vignette has also been chosen to focus on different governance contexts for irreversibility issues: in strategic policy, in project decisions and in decommissioning arrangements. The UK is a valuable context for our concerns, because the country has seen the steady expansion of onshore wind since the 1990s, such that increasing numbers of onshore wind farms are facing end-of-life concerns regarding how impacts should be handled [8]. It is also a country in which the environmental impacts of expanding wind power has often generated conflict.

5.0 Empirical vignettes

5.1 Considering reversibility in policy: permanent sites, reversible facilities?

The first vignette looks at how governments use policy to steer choices regarding the future of existing renewable energy facilities. Through applying our framework, one can see choices being made over the relevant benchmark, the values at stake, and the entities to which concerns about (ir)reversibility are applied.

Of all the devolved nations of the UK, Scotland has arguably given end-of-life issues for onshore wind the greatest policy consideration [8]. What is particularly interesting in Scottish policy development is that it has moved away from UK policy norms that negotiate impact reversibility largely through making project consents notionally time limited (typically for 25 years) with specified removal at the end of that period. As an additional step, the Scottish government has tried to steer the future, by acting on long-term expectations for wind farm *sites*, in ways that separate sites from the treatment of the infrastructure and its components.

In 2014 Scottish planning policy stated that ‘areas identified for wind farms should be suitable for use in perpetuity’[1]. This longer-term approach to sites was further developed in 2017 policy. Through such policy development, regulatory approaches that previously focused on time limits for infrastructure, and the prospects of removal and reversibility, now deliberately instituted an approach in which existing wind farms create a longer-term legacy for their site and wider environs. The motive lies in the Scottish Government’s consistent support for the wind energy sector, and a recognition that if installed capacity is to be maintained and increased over time then it needed to de-risk the prospects of repowering proposals on existing sites.

What one has in Scotland, then, is policy support for the idea that areas used for wind farms should do so irreversibly (at least for the medium term). The selectivity of this action is apparent from the way that policy is acting on the site – and thereby myriad socio-ecological relationships between wind energy exploitation and the wider area – but not necessarily on specific facilities. Wind farm facilities may be repowered or extended, causing an array of material changes with their own reversibility challenges arising in decommissioning [103–105], as we discuss below. Meanwhile, the repowering and life-extension of schemes is explicitly supported, with the 2017 policy stating that the government’s position ‘remains one of clear support in principle for repowering at existing sites[2], highlighting the benefits of repowering, including maximising ‘value for Scotland in terms of economic, social, and environmental benefits’[3]. Policy is, in effect, encouraging the kind of ‘land recycling’ observed for other energy facilities [20].

The effects of this change in policy can be seen with a 2019 repowering decision, for Tangy IV in Argyll & Bute, being granted a 50 year planning consent - significantly longer than previous norms. However, this case also reveals the broad spatial governance intentions of the ‘in perpetuity’ policy for sites but not facilities, as the Scottish Ministers refused to grant the applicants request for a consent in perpetuity. Their justification for doing so referenced another focus for irreversibility concerns – physical entropic and economic effects on the productivity of existing machines [61], viz.:

> ‘with continual advancement of technology and the production of more efficient wind turbines it is generally expected that these machines will be capable of producing electricity over a longer period. Nevertheless it is acknowledged in practical terms, that even with good practice in maintenance, wind turbine generators have a natural lifespan of operation’[4].

For infrastructural components of the *facility*, Scottish Governments seek to regulate prospective future (ir)reversibilities, and do so through keeping a time-limit in place and also attaching conditions that require removal of turbines that have not been working for twelve

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[1] Scottish Government 2014. Scottish Planning Policy, p170

[2] Scottish Government 2017. Onshore wind: policy statement. p35.

[3] Ibid. p11

[4] Scottish Government. Tangy IV determination letter, p19

months. In effect, they seek to control future impact legacy risks by containing the permitted life of the facility, but extend it for the site.

What is interesting in terms of (ir)reversibility is how the government has tried to avoid the volume of wind energy from declining over time, by securing the acceptability of landscapes for windfarms in perpetuity. It also reveals how existing developments have been regarded as changing the baseline of sites and the wider places they inhabit, with current sites being considered as appropriate for wind farm sites into the long term. One can see the choices entailed in negotiating and instituting concerns for (ir)reversibility in this way, including how the policy risks side-lining some concerns. It assumes that there is no societal interest in re-thinking the original siting of wind farms. This could be problematic, not least given the fast-paced nature of initial Scottish onshore wind expansion [106]. It may also cause disquiet for those who may have been anticipating the removal of infrastructure and restoration of a site after an initial time-limited consent. Instead, the prospect of impact reversal is open-endedly deferred. How publics may respond to such a prospect is illustrated by our next vignette.

5.2 Pressing for impact reversal – The challenges of reversibility in Kirby Moor

As we noted above, there is a body of research suggesting that over time publics become habituated towards the presence of wind farms in their local area, which has been used to infer that extending the life of an existing wind farm, or repowering, is less likely to generate public conflict than new projects on new sites. However, public acceptance of repowering or life-extension is not guaranteed, and there is much that could be learned – as yet almost entirely untapped – from those cases where publics do press for impact reversal. The case of Kirby Moor is one such example. This case reveals challenges and contestation involving a number of the key questions in our conceptual framework: the basis of judgement for impact (ir)reversibility, including the benchmarks at stake; the entities to be the focus of action, and the difficulties of securing regulatory control over potential long-term impacts.

Kirkby Moor wind farm is located just outside the Lake District National Park in northern England. The Sectary of State (SOS) granted planning permission for 15 x 45m turbines in 1992 for a time-limited period of 25 years and 12 such turbines were constructed, becoming operational in 1993. This time limit was linked explicitly to the experimental qualities of the project, presented by the SOS as the need to develop wind farms 'in different places to test their economic viability and environmental acceptability'[5] during an early phase of wind farm development. The 25-year duration was justified as it was 'considered that permission should be given for the project to proceed for the expected life of the turbines, after which they should be removed'[6]. Kirby Moor is thus a classic example of how the adverse landscape impacts can be rendered more acceptable, in part, because they are considered to be reversible at a specific point in the future.

However, UK planning regulation enables significant discretion. After two decades of operation, an application to repower the site with six larger 115m turbines was submitted in December 2014, but refused. Subsequently, an application to extend the life of the existing scheme for 8.5 years was submitted in August 2017 and also refused. The developer appealed the refused life-extension and the appeal was granted in July 2019. The repowering and life-extension applications faced a high level of opposition, from the public and from countryside

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[5] Kirkby Moor Sectary of State (SOS) decision, March 1992.

[6] Ibid.

protection NGOs. The location was one key factor (being near to and highly visible from the Lake District National Park) but so, too, was the planning condition imposing the time limits. For opponents, the prospect of breaking this ‘promise to the future’ [107], of not removing the scheme after 25 years, intensified their opposition.

Also complicating the decision was the political economy of site restoration, affecting the realities of regulating future impact reversibility. The original consent imposed conditions requiring removal of the turbines but not the associated infrastructure such as transformer substations, cabling, concrete tower bases and access tracks. There was no legal onus on the developer or any other party to remove these items, risking their abandonment on the moor. This created a situation for both the repowering and life-extension applications where the developer was able to offer improved decommissioning, site restoration and habitats enhancement as part of their new schemes. Such issues were closely considered in the decision-making processes, with claims about reversibility invoked. The life-extension committee report identified that landscape effects were ‘non- permanent, provided the development is removed and the restoration plan completed[7]’. The choice between partial removal after 25 years versus more complete removal in the future proved finely balanced, and highly contested, with the appeal inspectors ultimately siding with developers:

> ‘overall, the continuation of the life of this windfarm for a further limited period would provide benefits in terms of the production of renewable energy and would include decommissioning and restoration advantages. These matters outweigh the limited harm which the proposal would cause for the remainder of the life of the installation[8]’.

One can see how the key questions surrounding impact (ir)reversibility from our conceptual framework unfolded in this case. We see the selectivity inherent in claims of impact reversibility in relation to the entities deemed to be of concern i.e. how many components of the existing facility can operators be obliged to remove? We also see objectors presenting the pre-windfarm landscape as the appropriate long-term benchmark for judgement, and resisting a temporally-extended wind farm landscape. Here the benchmarks are linked to different considerations about the future use of the site. But we also see how political-institutional questions about how societies seek to regulate future impact 'reversal' can be just as problematic as disputes about meaning. Here the renewable energy sector exemplifies tendencies noted in neo-liberal political economies more generally, in that dealing with the dereliction risks externalised by earlier, less well-regulated rounds of economic development is highly dependent on allowing further, profit-generating activity i.e. the existing development creates a particular path dependency, shaping the future of the site. The UK has numerous cases where opencast coal mining has been justified in relation to restoring the dereliction of previous deep mining [108]. Such dependencies on economic viability create risks for decommissioning, as considered next.

5.3 Decommissioning and (partial) reversibility

Our final vignette further demonstrates that selectivity and partiality is inherent to the pursuit of reversibility ‘in the field’ through exploring treatment of these questions in decommissioning policy and practice. There is little consistent practice for managing decommissioning for onshore wind farms in the UK [105,109]; a similar situation prevails

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[7] Kirkby Moor life-extension committee report, 2017,45.

[8] Kirkby Moor appeal decision, 2019, 93.

elsewhere in Europe [110] and in the U.S. [12,54]. As this vignette will show, the treatment of reversibility issues within decommissioning practice – what it covers and its limitations – also reveals the connections between (ir)reversibility and concerns for environmental value and future generations, particularly deliberation of whether some irreversible effects should be a legitimate public concern.

We have noted above that analysts often assume the easy removal of wind farm infrastructure without long lasting impacts, yet in the UK any such ease is realised by selectiveness. Common practice for decommissioning is not to enforce total removal, but rather to remove all visible impacts, with concrete foundations only removed to one metre below the ground surface [103]. Such removal is promoted as sufficient to enable sites to easily return to their previous condition following decommissioning – usually captured in agricultural and visual impact terms [19]. Such selectiveness has some potentially problematic omissions. Welstead et al.[104], in their study of Restoration and Decommissioning Plans (RDP's) for Scottish wind farm sites, noted how such conventions omit the ongoing existence of subsurface cables and concrete foundations. Such residual debris may accumulate on sites subject to successive repowering, where bigger, differently-positioned turbines generate new foundations and connections, with ecological and hydrological consequences. These sub-surface problems may accumulate in sensitive landscapes such as areas of deep peat, increasingly valued for their function as carbon stores [103].

There are further complexities here. As with offshore environments, the merits of pursuing further impact reversal may be outweighed on environmental grounds, if removal of subsurface components – perhaps involving digging up cables in remote environments - was thought potentially more damaging. In addition, many wind farm developments in the UK have contributed towards on-site habitat enhancement, to mitigate the potential risks to wildlife that these facilities may create while in operation [111]. Such measures also raise questions about whether returning such sites to the status quo ex ante is the appropriate benchmark; and what happens to those environmental enhancement measures once the development – and funding – ceases.

The legislative requirements for decommissioning plans imposed by the UK on offshore wind farms [112] have no equivalent onshore, where national planning policy is limited in its treatment of decommissioning. To take the example of England, planning policy guidance simply states that planning conditions attached to consents should be used and the land should be restored to 'an appropriate use.'[9] There is no detail regarding what constitutes an 'appropriate use' or how this should be assessed. Such a position may reflect government preferences to defer details to local-level decisions. The openness of policy may also reflect another facet of debates about irreversibility, in the economic sphere: the desirability of avoiding premature action and facilitating flexibility, in the context of uncertainty and prospective technological change [23]. However, there is also the risk that an unwillingness to 'pre-commit' the future [23,96] contributes to the present-time invisibility of decommissioning issues.

This is a live risk, because, what little research exists suggests that securing decommissioning in practice hangs on a number of judgements: that developers will choose to be responsible, that there will be a market that justifies material recovery, or that decommissioning can be legally enforced [8,12]. There are reasons to treat these judgements as precarious.

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[9] UK Government. National Policy Statement for Renewable Energy Infrastructure (EN-3), 2011,2.7.17.

Dependence on the existence of effective market opportunities as a mode of regulation is problematic. Second-hand markets may provide incentives to encourage removal of some turbines [113], but our literature review suggested that any 'circular economy' for turbine materials is at a fledgling stage, with recycle value much shaped by price competition with virgin materials [52,53]. It is more difficult to envisage how markets could develop for other elements such as foundations, access roads or grid connections, especially given the often remote locations [49,54]. The use of legal planning agreements may be able to hold facility owners and operators to land remediation and habitat restoration actions; however there appear to be no studies assessing the ultimate efficacy of such planning agreements in the UK renewable energy sector.

There are examples of wind turbines remaining in place, apparently abandoned, after their operational life [52,98] and the potential for infrastructure to be abandoned is an issue that has been raised by wind farm objectors, most notably in the United States [54,114,115]. Renewable energy sector representatives are keen to stress that their members adopt sound practices, with the European Wind trade association calling for a European Standard for decommissioning [110]. However, history suggests that most energy technologies have a finite life, and that their end comes with a collapse of economic worth, a tendency for private sector actors to minimise and avoid hard-to-afford liabilities, with a concomitant offloading of responsibilities onto an often over-stretched public purse. Nuclear power, oil and gas drilling [54] and coal all exemplify this tendency [3]. Such 'reference cases' may shine a valuable light on how impact irreversibility risks may be managed for the renewable energy sector.

History might cause us to propose different benchmarks for renewable energy, which question whether complete removal is necessary: irreversible effects may be unavoidable, but not necessarily malign [22]. Various studies have shown how, over time, disused and abandoned industrial structures can be powerful activators of social memory and place identity, even within rural settings [20,116,117]. This could be the fate of remnants of renewable energy facilities; perhaps especially given the various positive, symbolic connotations of such technologies. However, one must handle carefully the notion that long-term effects from redundant renewable energy facilities are unproblematic because they might become tomorrow's interesting heritage: consideration of both existing and future users of the site is important here. As Sagoff [27] remarks, we are not just responsible to future generations (in the environment that we leave them), we are responsible *for* them, in that we should seek – through our acts – to convey values we would like them to adopt. Displaying a 'time-scale of concern and responsibility … equal to the life-time of our creations and their effects' [63, p.166], is one value we may wish to transmit to the future.

6.0 Conclusions

In this paper, we have examined the often-made claims that the impacts of renewable energy technologies – such as onshore wind – are reversible. This is an important subject, as arguments about legacy effects will grow in significance as installed capacity increases and existing facilities inexorably age. Research confirms that the risks of irreversible effects from renewable energy technologies are modest in comparison with fossil fuel or nuclear systems, but it also confirms that they are not trivial. It is no longer sufficient, therefore, to defer to broad claims about 'potential reversibility'.

Our first contribution is to have provided the first significant review of existing research that bears upon impact (ir)reversibility in the context of renewable energy, with particular reference to onshore wind. Through combining elements of systematic and narrative literature review, we have shown the limited and patchy nature of existing work. There are clusters of published research that focus on aspects of the long-term and end-of-life impacts of renewable energy, notably: life-cycle analysis; offshore wind-farm decommissioning, and emerging interest in turbine recycling. However, many articles tend to analyse the problem in abstract, dis-embedded terms, as detached flows of materials and embodied emissions rather than spatially, socially and ecologically-embedded facilities. This matters because the interface between actual facilities and contexts – places, landscapes, ecosystems - is precisely where questions of impact (ir)reversibility become messy, potentially controversial and may generate widest societal interest. The reviews also showed that we are only just starting to develop policies to address many of the environmental and social impacts created by renewables [118], with much literature referring to potential, hypothetical, 'good practice' strategies.

Our second contribution is to develop a conceptual framework for investigating the prospects of achieving impact (ir)reversibility for renewable energy development. This draws on a central finding from our literature review. Whether renewable energy facilities are 'reversible' in their impacts is not a binary 'yes' or 'no' issue that commonplace assertions might suggest: rather, claims are bound up with wider ontological and value positions, which can enable or foreclose the prospect of impacts being meaningfully reversible. This conclusion does not imply that answers to the question 'are the impacts of renewable energy reversible?' are all relative. Rather, our analysis shows that claims about impact (ir)reversibility, and what they legitimise, are inevitably selective, but with important material and social consequences. This selectiveness needs to be more visible and explicit. In our conceptual framework we identified the key questions that require attention when investigating impact (ir)reversibility: the basis of judgement; the entities of concern; the allocation of responsibility; the mode of regulation; and the scale of possible long-term effects. The salience of these questions was demonstrated through the exploration of three empirical vignettes. The framework may also have relevance for – and allow for comparison between – different categories of development (energy, transport, water engineering etc).

These conclusions also apply to key analytical techniques like LCA, which either need to better acknowledge their own selectivity with respect to site-based impact issues, or find better ways of embracing the reality of end-of-life practices. This may include a greater consideration of the decommissioning stage including how land is restored (or otherwise) and the scale and extent of any enduring impacts.

In the focus and execution of our analyses, we have been particularly mindful of the actual and prospective contribution of the social sciences. Despite the methodology adopted for our literature review, the searches revealed a particular dearth of research-based social scientific contributions. This is problematic, especially given the vital importance of understanding the ways that claims about (ir)reversibility are constructed and mobilised. There is an important research agenda for the social sciences in understanding claim construction, and analysing which conceptions of (ir)reversibility gain traction, becoming institutionalised in governance arrangements and, as a consequences, which long-term legacy effects get addressed and which get marginalised and/or treated as acceptable.

However, it is also clear that 'reversibility' and 'irreversibility' are not exclusively social science concepts, but rather better understood – like many component principles of sustainable development – as trans-disciplinary in nature, in that they demarcate an analytical terrain to which many disciplines can contribute. This much is already apparent from the diverse disciplinary bases and subject matter of existing research identified from the literature review. On this basis, we suggest the following research agenda:

Focusing more on what is happening in practice. To better understand the potential long-term impact risks from renewable energy there is a need to supplement abstract research about potential strategies for making impacts reversible, with evidence-based research about what is happening with end-of-life decisions on the ground.

Pre-emptive action to reduce legacy effects. Renewable energy development cannot eliminate irreversible environmental impacts, but there is significant scope to pull together research into the diverse 'upstream' and 'downstream' practices that could make renewable energy development less prone to major irreversibilities. There are numerous candidates here, including avoiding siting facilities in locations embodying high and irreplaceable biodiversity and landscape values[65]; the development of more efficient technologies (in terms of energy conversion), thus reducing the ecological footprint of each unit of power delivered; designing equipment for ease of future recycling; re-use of site foundations in repowering schemes [37], and designing effective instruments for securing decommissioning that will retain their efficacy over time.

Collaborative research across different disciplines and cognate problems. Alongside greater input from social scientists, there is a wider need for renewable energy scholars to engage with researchers working on cognate problems in other fields, and in other disciplines. One obvious area is the large literature on ecological restoration, which already brings together the interests of environmental, biological and social scientists, and offers insights on both the contestation of benchmarks and the social and policy processes governing restoration in the field [68]. Another important area for collaboration is to link with analyses of what has happened to other energy sectors when they start to decline, and in particular what happens to their legacies and liabilities. Researchers can address the factors, contexts and measures that have affected whether long-term impacts are effectively managed or not, and ask whether these factors might also apply to renewable energy. Forewarned is forearmed.

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