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Citation for the original published paper (version of record):
Ahlborg, H., Ruiz-Mercado, I., Molander, S. et al (2019). Bringing technology into social-ecological systems research-Motivations for a socio-technical-ecological systems approach. Sustainability, 11(7).
http://dx.doi.org/10.3390/su11072009

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Review

Bringing Technology into Social-Ecological Systems Research—Motivations for a Socio-Technical-Ecological Systems Approach

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Received: 18 March 2019; Accepted: 1 April 2019; Published: 4 April 2019

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Abstract: The purpose of this synthesis paper is to present the motivations and conceptual basis for research on socio-technical-ecological systems (STES), addressing the need for interdisciplinary studies targeting the technological mediation of human–environment relationships. The background is the very limited number of collaborations between scholars of social-ecological systems and sociotechnical systems (SES), despite repeated calls for bridging work. The synthesis builds on an in-depth review of previous literature, interdisciplinary exchanges, and empirical examples. The result is arguments for why a sociotechnical understanding of 'technology' is of central importance for SES studies, related to how technology: (1) mediates human–environment relationships; (2) brings ambivalence to these relationships; (3) enhances and transforms human agency and provides a source of constitutive power; (4) changes scalar relationships, enabling our interaction with and impact on the natural world across time and space. Furthermore, we present an STES analytical approach which starts from symmetrical attention to technology, society, and environment, specifically targeting interfaces and relationships of critical relevance for SES scholars, and address counterarguments that we have encountered. We conclude that a shift to STES research will enhance our knowledge of system interfaces that are often overlooked, opening further avenues for research and real-world interventions.

Keywords: social-ecological systems; sociotechnical systems; STES; SETS; Anthropocene; technology; review; synthesis

1. Introduction

Currently, we are witnessing a number of global environmental trends that are not promising for the future. Accelerating climate change, loss of biodiversity, chemical pollution, disappearance of natural forests, and degradation of fishing grounds and agricultural lands are just a few of the serious environmental problems that threaten the functional and structural integrity of ecosystems, to an extent that also risks the collapse of human societies. The scale of human impact—which has been greatly increased by technological development—is now such that some scholars suggest that we live in the Anthropocene [1]. The consumption and production of materials brought by the current economic model is increasing (e.g., for plastics see [2]), at the same time as access to basic goods and services in many societies is becoming increasingly unequal [3,4].

The trends are driven by several linked factors, which are not easily disentangled into manageable specific problems to be solved by specific policies. The complex nature of the phenomena requires that researchers who aim to inform policy making collaborate across disciplines and with societal stakeholders in order to address the challenges in an effective and realistic manner, while also being aware of the plural ways of understanding and evaluating more specific situations. We need to understand not only the respective phenomena in depth but also the systemic nature of these and the various kinds of relationships that link them together.

We perceive society, technology, and environment as co-constituted and co-emergent entities, what we may call a nexus [5]. In recent years, scholars who are active in the sociotechnical research domain have engaged with the literature on social-ecological systems (SES) [6,7]. In parallel, scholars in the SES field are calling for more attention to technology and the built environment [8–10]. As these scholars highlight, bridging across the two fields requires careful conceptual work and both theoretical and more practical collaboration. Unfortunately, the calls have not yet resulted in much joint research and theoretical advances regarding this nexus. In our experience, among the things that hinder ground breaking collaborations is an unwillingness in the SES community to engage more profoundly with technology as a mediator of human–environment relationships. We propose that this is due to, first, a lack of knowledge on how to go about integrating technology in conceptual and analytical frameworks, and second, a view of technology that is static and/or determinist. A similar lack of interest and knowledge is present also in the sociotechnical systems (STS) community when it comes to dynamic and complex social-environmental phenomena.

With this paper, we intend to clarify both the motivation and conceptual basis for research on socio-technical-ecological systems (STES) rather than social-ecological (SES) or sociotechnical systems (STS) separately. The general, and possibly provocative, argument is that when scholars are aiming to address complex and interlinked phenomena at the interface of human society and ecosystems, then an accurate understanding of causal relationships is only possible if there is understanding of technological mediation of human–environment relationships. We qualify this argument by synthesizing insights from existing literature and developing an in-depth conceptual argument around the motivations for work bridging and combining the SES and STS approaches. Enhanced cross-field dialogue around a nexus of social-technological-ecological systems studies can bring important insights for both research and policy. In our experience, the learning goes both ways and requires careful listening and attention to the diverging and sometimes conflicting ontological and epistemological positions.

The discussion is organized in terms of reasons why technology should be integrated into SES (although outside the scope of this paper, we think a parallel discussion is necessary regarding the importance of STS scholars paying more attention to environmental dynamics), which together amount to an understanding of technology and its interactions, specifically focused on the interfaces most relevant to SES studies. In relation to previous literature that engages with the need for bridging across the SES and STS fields, this synthesis takes several steps forward and contributes to the conceptual basis for framings that allow for a symmetrical consideration of society, technology, and ecology.

Our main arguments for suggesting this bridging work are based upon four aspects of technology: (1) interface and mediation, (2) ambivalence, (3) agency and power, and (4) scale. The aspects are the result of our own collective work process and we identified them intuitively as we started to unwrap the layers of our own understandings of technology and human–environment relationships. They are related to how we understand and characterize the 'systems' we study, and they are, in that sense, ontological. These aspects suggest a shift in the ontological understanding of coupled human–environment systems, which has consequences for research practice and epistemology. Consider, for example, the aspect of scale—it cuts across the characterization of how 'systems' work, what we think we know about them, and how we propose to study them.

We consider the consequences of a shift from SES to STES and what it demands of us in terms of the framing of research—here broadly conceived as involving problem formulation, choice and development of analytical frameworks, and methodological choices—and the political implications of this shift [11,12]. This is only the start of a longer conversation. However, we go beyond the general arguments and outline key features of an STES approach, providing novel guidance on how work on STES can advance in a way that tackles critical issues regarding epistemological tensions, problem definition, choice of system boundaries, and scale of observation, and the role of an STES research in relation to governance and policy. Finally, we take seriously critique from SES scholars and provide answers to counterarguments against the approach we advocate.

We have organized the paper in six major sections: first, the Introduction, second, the Materials and Method section. Third, we present two key concepts of relevance to our argument—Anthropocene and technology—and provide the reader with a short description of the respective fields, SES and STS. Fourth, we engage with the four reasons for working on STES. Fifth, we outline our approach and consider some of the consequences a STES approach has on aspects of framing, some conceptual challenges thereof, and reflect on counterarguments we have encountered. Finally, we conclude.

2. Materials and Method

This conceptual contribution to an on-going larger integrative research process relies on several parallel activities. The synthesis of multiple scientific fields and strands of thought is based on literature review, interactions with colleagues in personal communications, seminars and conferences, and reflections.

The literature review was structured similar to the technique of snowballing in interviews: we started from some key publications that explicitly discussed integration across the SES and STS fields. The lists of references led to the identification of further relevant texts. We combined this with searches on Google Scholar using combinations of terms, such as 'technology', 'social-ecological systems', 'sociotechnical', 'STS', 'SES', 'STES', 'SETS', 'infrastructure', and 'resilience'. We also reviewed literature, describing and comparing analytical frameworks for studies of social-ecological systems and 'coupled human–environment systems', articles on the concept of 'Anthropocene', and a number of frameworks used by sociotechnical scholars working on so called 'sustainability transitions'—a subfield of STS that explicitly tackles prospects for sustainable development and addressing human environmental impacts.

A difficulty regarding scope is that the acronyms SES and STS signify multiple things and both fields are potentially very large and interdisciplinary. This creates tension between what audience we engage, what literature we draw on for the synthesis, and what sub-fields we propose should integrate. Hence, we are proposing an understanding of technology that draws on multiple writings from a wide and loosely defined sociotechnical field, including philosophy of technology. But when we argue for integration across the SES and STS fields, then we have primarily two specific sub-fields in mind: first, the subfield of sustainability transitions (this growing community of scholars meet, for example, at the International Sustainability Transitions (IST) conferences, and has the Sustainability Transitions Research Network (STRN) https://transitionsnetwork.org) and, second, the social-ecological systems framework that has emerged from the encounter between ecology and political science [8,13,14]. These subfields share a base in systems thinking and an interest in sustainability, creating a clear interface for bridging work.

The conflicts between different epistemologies challenged us as we embarked on writing this paper, especially the incompatibilities between realist and constructivist positions. We are not able to overcome this divide, but we try to work constructively with the tensions. Our own position is agnostic in the sense that we acknowledge that our understanding of the world is achieved through and constructed by our cognition and, hence, we need always be wary of our mental models and biases. As we speak about the world, phenomena, complex systems, and processes, we realize there is no access for us to the world as it is beyond our own cognition, but still insist on the meaningfulness of working to understand the world as best we can through careful investigation, using a plurality of perspectives and methods. We accept our position—that we are part of the systems we study. In our experience, complex systems theory provides a vocabulary that enables a dialogue across the rift of realist versus constructivist views, when one combines it with careful listening and humility (for example, [15]).

3. The Anthropocene and Technology

Crutzen and Stoermer [1] proposed that we live in "the Anthropocene"—a concept meant to highlight the extent to which the current geological time period is human influenced, or anthropogenic. Although the Anthropocene is still to be accepted formally as the current geological time period and no consensus exists as to when the period started, the concept is increasingly used to emphasize how important and large the human impact on nature has become, to the extent that human societies are altering "atmospheric, geologic, hydrologic, biospheric, and other earth system processes" [16].

In this line of thought, the Anthropocene is characterized by the "expansion of mankind, both in numbers and per capita exploitation of Earth's resources" [1] (p. 17). Our activities are reshaping the conditions for life on Earth. Natural science evidence indicates that our impact is especially significant when it comes to climate change, loss of biosphere integrity, change in land systems, and altering of the biogeochemical cycles for phosphorus and nitrogen [17]. The concept reflects that human activity is considered the major driver for changes in the Earth system, as evidenced by how socio-economic trends are related to changes in the Earth system's structure and functioning [18]. The Anthropocene concept has challenged disciplinary research and led natural and social science and humanities' researchers to produce new transdisciplinary approaches for collaboration [19,20]. The concept has also drawn heavy critique from critical social science perspectives, including from STS scholars [21–23].

When reading the SES literature, we were struck by a contradiction—while technological innovation is attributed a critical role as the main driver for changes that characterize the Anthropocene, at the same time, explicit attention to technology is missing in the large majority of SES studies. Suggestions made and visualized on a time line [24] regarding the initiation of the Anthropocene include many human activities made possible by technological innovations. The many suggestions include: Megafauna extinction due to early weapons and hunting strategies; development of farming, e.g., large-scale rice production and anthropogenic impact on soils; colonization and associated migration of species; the industrial revolution; the beginning of the atomic age; and the "Great Acceleration" from the 1950's and onward [24]. In various ways, these innovations are part of the processes that explain the accelerating curves depicting human impact on the Earth system. However, the identification of specific innovations and historical events as the 'start' of a time period of human domination runs the risk of being simplistic and determinist in its understanding of technology, as well as Eurocentric in its historical view. It may also lead to nostalgia over an imagined pre-technical past when humans lived in harmony with nature [25]. In contrast, historical and sociological technology studies portray technological innovation as a process that is fundamentally complex, uncertain, socially embedded, and full of socio-political tensions [26,27].

As with many aspects of human culture, 'technology' changes character depending on our level of analysis. As a starting point for a dynamic and sociotechnical view, we define technology in line with Arthur [28], as a means to fulfill human purposes. As a means, 'technology' may be a method, process, or a device—normally combining software and hardware—used to execute purposes and supply functionalities. Among the many different definitions and conceptualizations of technology in the literature, we find Arthur's definition sufficiently broad since it includes more than artefacts, but also it is sufficiently narrow that not everything created by humans is labelled as 'technology'. We prefer to see institutions and culture—both of which can be seen as a means to various purposeful ends—not as technology but as different phenomena (although a great number of technologies are made use of in cultural activities and institutions, and vice versa). These "purposed systems" are also a means to fulfill purposes, but they differ from what we normally think about as "technology" in that they, primarily, harness a behavioral or emotional phenomenon. Arthur considers these to be "cousins" of technology [28] (p. 54). Hence, Arthur proposes that technology involves the harnessing of phenomena of nature, that is, technology is purposeful action for exploiting physical phenomena or effects. These are organized in a planned way and orchestrated for use. This definition places the focus on practices—what creators, designers, technicians, managers, and users of technologies do, what the sociotechnical systems may cause, and how these arrangements, practices and implications evolve. We propose this as our working definition because we find it fruitful analytically (as a heuristic) given the type of systems we are trying to make sense of.

There are no clear and simple boundaries of technologies, and often, they capture and put to use a collection of phenomena, both physical and behavioral, to a plurality of purposes. Arthur's distinctions do not imply that technology is separate from society, on the contrary, he sees technologies as based on human cognition, human knowledge, and human motivations, hence they are always socially constituted. Furthermore, as we zoom out from individual artefacts to larger systems and networks, the planned character and complicatedness of interacting components is rapidly replaced by complexity [29]. Complex systems have properties of self-organization [29,30], that is, they are able to structure themselves, create new structures, to learn, diversify, and become increasingly complex [31–33].

The argument that technology is socially constituted is widely known today. Feenberg [34] (p. 17) argues that the "social dimensions of technological systems belong to the essence of technology . . . ". Although various technologies are commonly judged according to how efficiently they execute a purpose, technology is underdetermined by the criterion of efficiency, it is shaped by and responsive to a plurality of interests, meanings, ideologies, and needs [35]. As historical empirical studies of the development of technologies show, social choices influence the problem definition, the perceived solution, and the process of design and adaptation [36]. In the encounters between technologies and society, between artefacts and humans, between planned purposeful harnessing of phenomenon and messy social life, sociotechnical systems are fluid, imperfect, and contingent. They are complex adaptive systems [37,38].

3.1. Sociotechnical Systems Approaches and Ecological Dynamics

In order to clarify the potential for bridging between the STS and SES fields, the fields need a brief introduction. In contrast with earlier notions of technology that saw technology as an autonomous force outside human control, in its essence destructive, or as neutral means to separate ends, the field of sociotechnical studies centers on an understanding of technology as socially contingent and a terrain of struggle with socio-political consequences [7,26,34]. In this view, society and technology are mutually constitutive—social processes shape the development and use of technology, but technologies in turn embody power relations and come to constitute our lifeworld, reshape our social interactions and practices in society. "New technologies . . . arise through active development, linkages, and the alignment of heterogeneous, social, and technical elements into working configurations." [7] (p. 12). The direction of innovation and technological change is influenced by a multiplicity of actors, political and economic interests, and contextual conditions [27,30,39]. Relationships of power and sociotechnical change shape each other, and technologies can be redesigned and reconstructed, enabling redefinitions of the needs and purposes they meet.

Sociotechnical scholars have delivered important critiques of simplistic and determinist understandings of technology, whether these are technology optimistic or pessimistic. Among the multiple analytical perspectives that can be commonly identified as sociotechnical, we focus here on the current discussion on 'sustainability transitions', given its interest in the evolution of human–environment relationships. The sub-field is, so far, dominated by a few theoretical approaches and empirical work on energy systems and water infrastructure, but the theoretical and empirical scope is broadening. Two distinct analytical perspectives have emerged as significant—the multi-level perspective and the innovation systems approaches—but increasing attention is being given to other sectors, technological fields, and geographical contexts, including outside the few Western countries that were initially in focus [40–42], processes, actors, networks, and innovation at local and global levels of organization [43–45], and also practices rather than sectors as a starting point [46,47]. The disciplinary backgrounds of scholars who engage in this sub-field are diverse, including the history of technology, sociology, industrial and evolutionary economics (the forerunners include Joseph Schumpeter [48] and Christopher Freeman [49], who focus on innovation and technological change and its diffusion as important factors of societal development) and management studies, geography, political science, and cultural studies (for overviews see [30,50]).

However, sustainability transitions research generally lacks more specific accounts of ecosystems dynamics, their functions and their role in transitions. In our view, most work so far on sustainability transitions neglects and 'black-boxes' ecological dynamics (for exceptions, where sociotechnical and ecological perspectives are equally considered, see [46,51]). The literature refers to the ecological domain mainly in terms of the economy's natural resource base and as environmental problems caused by human activities (i.e., as inputs to and outputs from STS). Emissions of greenhouse gases receive far more attention than other (yet still connected) environmental challenges of decisive importance for human societies (e.g., biodiversity loss and degradation of lands). The connections to the ecosystems where the technical systems are embedded are often invisible in analytical frameworks, and the strong focus on actors is not matched by attention to the technical interfaces between them and ecological systems. Ecological dynamics, and how processes in nature modify and reconfigure sociotechnical configurations, are largely left out of research framings. We see great potential for SES and STS scholars to collaborate, given the shared interest in environmental change and sustainability.

3.2. Social-Ecological Systems and Technology

Studies of social-ecological systems, or coupled human-ecological systems, engage scholars from many backgrounds and fields. The coupled human-environment system is a central concept for a variety of approaches and conceptual frameworks that engage with human–environment interactions. According to a review by Binder et al., these approaches "differ significantly in their goal, their disciplinary background, their applicability, the temporal, social, and spatial scale addressed, and their conceptualization of the social and ecological systems as well as their interaction", and there is little guidance on how to apply them to a specific research question [52] (p. 26). One of these approaches is the social ecological systems framework—what we here refer to as SES—as developed, on the one hand, in ecology [13,32,53] and, on the other hand, in political sciences, by Elinor Ostrom and colleagues [8,14,54]. This approach is widely used in order to explain (un)sustainable outcomes in the management of various resource sectors, e.g., forestry, fishery, and water resources. As Binder et al. [52] indicate, the SES framework is the only one of the ten they reviewed that is framed so as to allow an equally deep analysis of the two major components—society and ecology. We see this analytical symmetry as a strength. Furthermore, SES has a strong base in systems thinking (see [32,54]).

SES are framed as complex adaptive systems [53,55], i.e., nested, multilevel systems with various feedback loops between a multitude of entities, making adaptation on different time scales possible and their behavior hard to predict. Human-environment systems, like the agroecosystems that provide essential services to society, such as a supply of food, fiber, bioenergy, and drinking water, are examples of such complex adaptive systems.

In recent years, SES scholars have started to call for more attention to technology, and the way human-built infrastructures play a key role in ecological change and in relation to resilience and adaptability. According to Folke et al. [13] (p. 42), "Social-ecological resilience is the capacity to adapt or transform in the face of change in social-ecological systems, particularly unexpected change, in ways that continue to support human wellbeing . . . . Adaptability refers to human actions that sustain, innovate, and improve development on current pathways, while transformability is about shifting development into new pathways and even creating novel ones." Redman and Miller [10] (p. 270) argue that "there are fundamental discontinuities in the way we come to understand and manage social, ecological, and technological issues. More specifically, we contend that those concerned with sustainability and earth stewardship must more robustly account for the centrality of technology in human–environment interactions, adjusting our conceptual frameworks to explore socio-eco-technological systems".

In a similar line of thought, Anderies writes: "As the scale of human activity grows, and with it the scale of human-made infrastructure, understanding the built environment as embedded in a broader natural system becomes increasingly important. The interactions and feedbacks between the functioning of built environments and the biophysical context in which they operate can no longer be ignored." [8] (p. 130). For Anderies, the problem is how to design infrastructure so that self-organization at multiple scales, and hence resilience, is embedded into the built environment.

We agree with Anderies' call for attention to technology, as we find that there are very few SES studies that integrate technology in a more elaborated manner. This is understandable but, in our view, unfortunate. Based on our reading of SES literature, we find that SES scholars, if they consider technology in their analyses, generally treat it as an exogenous factor [13], as a passive background element, or as a tool [14]. There are of course exceptions (e.g., [56]), especially in the field of urban ecology, where scholars are developing new approaches, concepts, methods, and tools to integrate the built environment into social-ecological systems studies [9,57–59]. As Anderies writes: " ... we humans do not simply act on the environment. Rather, we act on the environment through built infrastructure ... " [31] (Section 3.2).

It appears to us that the SES field has, in general, lost sight of the role technology plays in social-ecological change, especially in the transformation of current dominant practices and development of new pathways, despite the attention paid to infrastructure in Ostrom's work on common property resources [60]. Anderies [8,31] uses the term 'infrastructure' in a wider meaning than what's common in SES, or even STS, literature. This definition includes both 'hard' and 'soft' infrastructure—'natural', 'built, 'social', and 'human' infrastructure. Both knowledge and institutions (rules of the game) are here classified as infrastructure. Other systems researchers, like Allen & Hoekstra [61], would use the even wider concept of "context" for the slowly changing parts of an entity's environment.

Ostrom and her colleagues considered the built environment as one of the elements that structure the "action arenas" where human–environment interactions take place [8]. However, we will write in the following section about technologies rather than built infrastructure for two reasons: first, because attention to the built environment does not capture the scope of the technologies involved or the extent of their interconnectedness; and second, because many people associate the word infrastructure with something fixed in place, which is more or less static.

To exemplify, consider for example our systems for food production, processing, and distribution. These are intertwined with many other sectors in society—water systems for irrigation and processing, energy systems, transport systems, industrial processing of agricultural inputs into consumer goods, business, culture, family life, health, and national security. A range of technologies work behind the scenes to support the adaptive change of the global economic system for food production in different and new directions. From the farm to the table, food currently goes through a very complex and large-scale technological system involving: sophisticated biotechnologies—including GMOs—for seed production; GPS assisted mechanized farming to guide fertilizer and pesticide application, as well as farm operations and harvesting; complex logistics and cold chains that move produce over thousands of kilometers (and lead to the waste of edible food in every step); high-end technologies for packaging, tracking, and food processing that extend produce shelf life (and increase the ecological footprint) and create an ever increasing variety of (mostly) highly-processed food that radically affects our health (e.g., [62,63]).

Considering systems for food production, we propose that a STES framing can complement the current analyses of the social-ecological dimensions of the sector's consequences for ecological integrity and ecosystem resilience, by further investigating possibilities for transforming the dominant system—or regime—of industrial and large-scale socio-technical-ecological food systems. Such an analysis requires a dynamic understanding not only of the agroecological systems and food markets [64,65], but also of the technologies at work in the sector, which enable production systems, value chains, and markets, and insights regarding the dominant sociotechnical norms and practices, dynamics of system stabilization and lock-in, as well as mechanisms behind the growth of new niches and the destabilization of dominant unsustainable practices and institutions [7,12].

3.3. Connecting Socio-Technical System Studies with Social-Ecological System Studies

Given the shared base in systems thinking, we see the potential for SES scholars to adopt a dynamic understanding of technology. As Smith and Stirling [7] (p. 11) write, both SES and STS are "understood to display complex, dynamic, multiscale, and adaptive properties; recommendations for their sustainable governance emphasize learning, experimentation, and iteration."

This leads us to believe that STS research can contribute many important insights regarding the potential for innovative and less environmentally destructive practices to emerge, which complement the important insights about ecological dynamics coming from the SES field. From a policy relevance perspective, collaborations between SES and STS scholars can possibly generate new insights and contribute to a transition to more sustainable societies.

The possibility of bridging these two fields has been discussed by others [5–8,10,66], but this is the first paper to propose an understanding of technology specifically for the SES audience and to outline an STES approach in enough detail to guide research collaborations. The topic of how society can embark on a more sustainable pathway is a focal point for joint work. As we have highlighted, the fields share many similarities at first glance, but there are important differences that call for a cautious approach. As Smith and Stirling write, "The focus of socio-technical transitions research is different from social-ecological systems research in a number of respects: objects, objectives, structure or function, and resilience and transformation." [7] (p. 13). Hence, there are challenges related to how to conceptualize and integrate across the fields, incorporating 'technology' as a key articulating concept.

4. Outlining the Arguments to Study STES

4.1. The Interface and Mediation Aspect of Technology

Since the early history of humans, we have used and created technology as means to various purposes. Starting with simple tools and artefacts made from natural materials, we have transformed natural environments and used natural phenomena for practical purposes of survival as well as for spiritual and social purposes. Our way of living in the world—through arrangements and interactions with everyone and everything around us—has undergone tremendous change throughout history. Our embeddedness has changed with the rearrangement and reorganization of our relationships and practices, increasingly achieved with and through different technologies [25]. With increasingly sophisticated harnessing of natural phenomena and innovative practices, sought in response to problems and possibilities in our lives, the webs of relationships we are part of have changed both qualitatively and quantitatively, socially and materially. One fundamental function of technology is as a means for humans to increase efficiency, safety, comfort, or control in relation to nature and other people, acting on the interface between humans and environment.

Technological change has accelerated over the course of human history, and with discoveries of new natural phenomena new spaces have opened up for human creativity and experimentation. The change is such that perhaps every basic human need in industrialized and urbanized societies is now mediated through a technical system: our transport, energy, and food systems; housing; clothing; cultural activities; even breathing relies on ventilation systems in most buildings, indoors and outdoors air pollution affects our health; drinking water in urban settings relies on systems channeling water from more or less remote drainage areas to potabilization plants, distributing it to users and, after use, to recipients of more or less treated waste water.

A consequence of this, as Brian Arthur has put it, is that: "Technology is steadily creating the dominant issues and upheavals of our time. We are moving from an era where machines enhanced the natural-speeded our movements, saved our sweat, stitched our clothing-to one that brings in technologies that resemble or replace the natural-genetic engineering, artificial intelligence, medical devices implanted in our bodies. As we learn to use these technologies, we are moving from *using* nature to *intervening directly within* nature." [28] (p. 11, our emphasis). This is not an entirely new practice, but the degree to, and scale at, which we are altering our own bodies, genetics, other species, and creating new materials is unprecedented. Our cognition is changing as technologies mediate our daily and scientific understanding of the world beyond our unaided senses, from the very small (e.g., nanotechnologies) to the very large (e.g., satellite imagery of the Earth).

As we see it, technology mediates (i.e., it shapes, enables, transforms, and conditions) our physical and symbolic interactions with our environment and other humans. In turn, technology, nature and human societies change throughout this process. This intermediary role of technology, together with its position at the interface between humans and our environment, is the reason why we place the 'T' between the social and ecological systems of STES.

The mediation aspect is at the heart of the complex nature of STES. As in other systems, such complexity first arises when it becomes practically impossible to simplify the elements and interactions, and when boundaries as well as causality are difficult to specify [67]. Systems thinking provides some tools for acknowledging complexity while making analytical representation possible [33], for example, through the critical act of setting system boundaries. Our argument here is that it is not possible to set a system boundary in a social-ecological system such that it decenters technology, because technology works at the interface and, to a large extent, shapes the kind of relationship humans have with their natural environment. Excluding 'T' from the system under study may render it invisible to the analyst, but its influence on the system dynamics—the interactions, feedbacks and emergent characteristics—is still decisive.

We suggest that a shift from SES to STES can account for technology-related dynamics in a way that avoids simplistic, reductionist, or determinist explanations. Also, policymakers care a great deal about technology and infrastructural investments, and, as argued by Redman and Miller [10], regularly make decisions that have direct and indirect impacts on ecosystems. The human population is still growing, more than half of us live our lives in cities, and our consumption of energy and materials shows an upward trend. Anderies writes: "The essential point here is that most mass, energy, and information flows relevant to human welfare are generated by a collection of different types of infrastructure. Thus, control action in SESs is concerned, for the most part, in investment in these sets of infrastructure." [31] (Section 3.2). Indeed, our society and economy are built on, with, and through technology, and to ignore its role as intermediary in social-ecological systems is to risk making oneself less relevant to other stakeholders in society, including political actors.

4.2. The Ambivalence Aspect–Technology as a Double-Edged Sword

We have seen that technology mediates more or less all of the interactions between humans and nature in societies around the world. Through these interactions, both humans and our environment are changed [34]. Humans are transformed, for example, by acquiring new skills and/or simply adapting to the new rules dictated by the daily operation of technological systems. At the same time, nature is humanized, creating a dynamic and complex society-technology-environment nexus. Technology is simultaneously a tool that can be put to different uses and an emergent social product, based on artifacts encapsulating physical, chemical, and biological properties, that bears the imprint of the society that created it. Technology can be a powerful means for domination, alienation, and mass destruction and at the same time a means for human liberation and environmental conservation. Technologies also reconfigure the space of human–human, and human–nature interactions in ways that could not have been predicted (for example, the internet or cell-phones). We argue, following Feenberg [68] (p. 14), that technology is an "ambivalent process of development suspended between different possibilities". This "ambivalence" of technology opens a space for multiple future configurations, that need to be explicitly acknowledged in SES and STS analyses as well as within current debates about sustainability transitions. Technological development is not neutral, but a space for conflict.

This understanding of technology is quite recent. Historically, two major questions have differentiated between views on technology: the extent to which humans control technology, and if it is neutral or value-laden. The view that technology belongs in the sphere of human action and ingenuity, where it works as a neutral means to achieve progress, is what Feenberg calls 'instrumentalism' and is still fairly dominant in the natural sciences and engineering. It argues that technology is neutral or universal, as it represents the embodiment of scientific principles and rational knowledge. Technical objects are then value-free, as they can be used to different ends, irrespective of the social-cultural context (a hammer is a hammer or a power plant is a power plant, and can be used anywhere). In this view, technology can thus be transferred from one place to another without problems. Negative effects of technology are acknowledged but supposed to be solved with appropriate regulation and economic incentives.

The second widespread view is what Feenberg [34,35] calls the 'substantivist' position (exemplified by Heidegger and Ellul). They perceive technology as value-laden, as having an essence of rational control and efficiency. Technology, thus, is inherently biased towards control and domination [69,70]. The substantivist position is determinist in that it sees technological advance as having "an automatic and unilinear character" that humans can only set limits for, but not reconstruct [34] (p. 3). In this view, modern technology (as opposed to traditional technology) is a "new type of cultural system that restructures the entire social world as an object of control" (see [68] (p. 7), citing the work by Ellul and Heidegger). Substantivists argue that the issue is not simply that machines have taken over, but that in choosing machines, or being forced to use them routinely, we make many unwitting cultural choices. Underlying this gloomy view is a dualism between efficiency and meaning. Substantivists assume that the analytical and professional separation of efficiency and meaning—that between the technical disciplines and humanistic disciplines—reflects an ontological distinction. From a sociotechnical viewpoint, this is to conflate "attitude with object, the modern obsession with efficiency with technology as such" [34] (p. x).

Given their widespread and problematic assumptions, instrumentalist and substantivist views merit our critical attention. They share a 'take it or leave it' attitude towards technology. If, on the one hand, technology is only instrumental and indifferent to values, then its design and structure is not an issue of political debate, only the range of its application. If, on the other hand, technology is the vehicle for cultural domination, then "we are condemned to pursue its advance toward dystopia or to regress to a more primitive way of life" [68] (p. 8). In neither case can we change the reason or action as embodied in technological objects—only the pace and type of technology development can be regulated, but not transformed. In contrast to instrumentalist and substantivist views, Feenberg's position is one of critical theory, and his work is inspired by, and has influenced, many sociotechnical scholars.

To recognize the ambivalence of technology is to see technology as value-laden and open to debate regarding its uses as means to a plurality of purposes, but also to the social values 'imprinted' in the design of technical systems. "Technology is not a destiny but a scene of struggle. It is a social battlefield or perhaps "a parliament of things" on which civilizational alternatives are debated and decided" [68] (p. 14). Dominant actors in society use technology to maintain and enhance their control and privilege, hence, "(w)here society is organized around technology, technological power is the principle form of power in the society. It is realized through designs which narrow the range of interests and concerns that can be represented by the normal functioning of the technology and the institutions which depend on it. This narrowing distorts the structure of experience and causes human suffering and damage to the natural environment" [35] (p. 49). However, in the hands of subordinate actors and based on other relations and values—such as nurturing and care, or possibly an ethic of 'stewardship' [13]—technologies can be redesigned to adapt to the needs to a more sustainable society [71]. Or, stated in a different way, a more sustainable civilization cannot emerge from ethics or ideology alone, without a deep restructuring of its technological base and the social relationships it reflects.

Within an STES (rather than an SES) framework, the ambivalence inherent in both the symbolic and material arena of sociotechnical change is something to be aware of, but not necessarily to consider problematic [72]. The potential for redesign and reconfiguration based on the contestation and reformulation of goals, needs, and pathways [73] opens up opportunities for decentering power over the tools, and for shifting emphasis and resources from political and economic centers to the everyday lives of people, to users' participation in technology design and use, and to maximizing instead of suppressing skills. STS discussions about technology include not only how to make it cleaner and more efficient, but how to democratize technologies and the work space (i.e., how to promote forms of decentralized control), exposing the very political nature of shaping technology. Also, discussions focus on how technology may serve to develop a diversified and context-based use of local resources and ecosystem services.

In short, we see potential for a fruitful dialogue on how "alternative technology" movements, such as grassroots innovations, social technologies, frugal innovation, and eco-technologies [74,75] relate to discussions taking place within the SES field on the need for technological innovation for social-ecological resilience [13].

4.3. The Aspect of Agency and Power

We argued above that technology mediates human–environment interactions in a fundamental way. We now wish to develop that statement further by examining first how technology relates to and transforms human agency and power, and thereafter what this means in terms of the scale of human impact on the natural world.

Human power is often defined as the capacity to act, what is called "power-to". As Lukes describes it, "having power is being able to make or receive any change, or to resist it" [76] (p. 69). The idea of human power as the capacity to create change posits that there is agency and a certain degree of freedom, also within the constraints of structural pressures [76]. At the individual level, our power or capacity to act is enhanced and limited by technology. Consider, for example, the way milling machines, powered first by the movement of water and later by diesel or electricity, enable a single or a few individual(s) to mill grains into flour much faster than would be possible with only a mortar and muscle power. But technology not only enhances or limits human power, it also transforms our physical capacities, even our physical body, our social standing, and ability to influence the world over time and space [77,78]. Our daily lives have changed due to many reasons: the way communication technologies facilitate our interactions with each other over time and space; how modern medicine is reshaping our biological structures; how artefacts lend us symbolic power by signaling our importance and status; and how weapons and security apparatuses allow individuals and collectives to surveil, threaten, control, and kill people who live nearby, far away, now, or in the future.

These examples highlight that our capacity to act is exercised in relation to someone or something. Rather than seeing power as a "thing" or "resource", we argue for a relational understanding of power [78]. So, if Arthur's definition of technology helps us identify what technology is and how it works, then Feenberg discusses the kind of relationship that technology creates between us and our environment, and its consequences: "Technical action represents a partial escape from the human condition. We call an action "technical" when the actor's impact on the object is out of all proportion to the return feedback affecting the actor. . . . the reciprocity of finite action is dissipated or deferred in such a way as to create the space of a necessary illusion of transcendence" [35] (p. 48). He exemplifies with the experience of driving your car fast while feeling secure and at ease listening to music. However, transcendence is an illusion. The consequences of our action of driving is that we become part of a larger system where our freedom and movement are restricted by road networks, traffic jams, and expenses for travel. Furthermore, this larger sociotechnical system influences the environment in a number of ways; roads fragment ecosystems and change run-off patterns, emissions from vehicles cause air pollution and contribute to climate change and human health impacts, noise disturb humans and animals, direct collisions take animal and human lives, etc.

Hence, technology mediates our interactions with nature in profound and very particular ways. The relationships change character as we zoom out from individuals to organizations, cities, regions, or international and global levels of organization. At higher levels, the transformative aspects of technology become perhaps even clearer. Technology makes centralized control over energy and resource flows possible, it constitutes the unequal distribution of wealth and political influence in the world. Recently, we are seeing the emergence of communication technologies and business models that create a decentralized but effective relationship of control between individuals and service providers at a combined micro- and macro-scale that was previously impossible. The relationship between hardware and software in electronic consumer products, the way apps create business dependencies with software updates, and how "free" social media platforms make use of user data to manipulate user behavior are some examples.

To Feenberg, the dominant mode of modern society is technocratic and one where "(t)echnology can be and is configured in such a way as to reproduce the rule of the few over the many. This is a possibility inscribed in the very structure of technical action which establishes a one-way direction of cause and effect." [35] (p. 48). To a large extent, it is people and ecosystems in peripheries that suffer the consequences of technical action in economic centers. However, the ambiguity of technology also opens up to other pathways and positive potentials, marginal people, and environments need not necessarily be the victims: "A different power structure would innovate a different technology with different consequences." [35] (p. 54). In our view, innovation aiming at the empowerment of marginalized people or driven by care and empathy is already and has always been present, even if the dominant mode can be argued to be one of exploitation.

These aspects of how technology transforms human capacity capture mechanisms of the intentional exercise of power, but in complex systems, dynamics include uncertainty and emergent, unintended consequences. The concept of 'constitutive power'—inspired by the work of Foucault—helps us analyze more elusive and 'systemic' pressures that work at the interface of society and nature [79]. Constitutive power emerges from complex and nested human–nonhuman networks and is felt as pressures without a clear human sender. Through technology, power is exercised by means of system configurations—a kind of encoding or translation of the exercise of power in hardware and software [80]. "Infrastructure embodies the intention of the designer, together with power encoded in the instructions for use. And this translation/embodiment/encoding is *a source of stabilization*, whereby human agency (that of system designers and engineers) is given a more durable form and condition spaces for action" [79] (p. 127). Importantly, the configuration is dynamic, as wilful users tend to modify, reinterpret and contest the prescribed 'proper' use of technologies and reconfigure the system [81]. Power embedded in infrastructure evokes responses and counteraction. What is often overlooked among STS scholars is how the modifications and reconfigurations are equally caused by processes in nature. In our studies of electricity generation and distribution networks, local topography, rainfall patterns, termites, winds, lightning, temperatures, soil erosion, and forest vegetation type influence the design, maintenance, and functionality of power plants and grids [82,83]. An example from Bangladesh shows how infrastructure built to control tidal flooding in deltas produce unexpected consequences as they also restrict sediment deposition on coastal floodplains, which would naturally sustain the elevation of coastal land, hence creating vulnerability to storm flooding [84].

The point we are making here is that the illusion of transcendence in technical action intending a one-way effect is often shattered as neither people and animals, nor ecosystems 'behave' according to plan. In fact, systemic pressures often arise from interactions between technologies and technology and nature, outside the realm of human agency. This suggests that an STES analysis would pay attention to three important questions not addressed by SES or STS alone: a) how technologies shape specific human–nature relations and with what consequences, for whom, and where; b) how emergent pressures in complex socio-technical-ecological systems are interlinked and; c) how intentional and unintentional technical mediation may result in ambiguous outcomes and feedbacks that shatter the illusion of transcendence. This brings us to the next reason for paying attention to technology: the aspect of scale.

4.4. The Scalar Aspect

When technology enhances and transforms human capacities it changes our temporal and spatial, qualitative and quantitative relations to our environment. The capacity for movement is greatly enhanced by, for instance, biking compared to walking, given there is a road or a path. Our capacity to do work changes with axes and handsaws, horses and plows, chainsaws, forest harvesters, tractors, and combine harvesters in agriculture. As we harness physical phenomena—gravity, nuclear energy, electromagnetic forces—and put them to use, we experience the cost and benefits of the technical efficiency that is so central to and cherished in our economy. Human action upon our environment has increased in scope, intensified, accelerated, and been extended in time and space, and also intervened at micro- and nano-scales, making control of physico-chemical processes at these scales possible. Technological change—and the various economic systems humans have shaped—has brought large, sometimes irreversible, shifts in societies' uses of natural resources and environments, and small, equally radical changes in physico–chemical processes.

The discussion of the Anthropocene draws attention to the capitalist economic system, with its logic of continuous growth—and associated increase in flows of energy and matter—which gains much of its durability and strength through sociotechnical configurations. The majority of shifts in terrestrial and aquatic environments are today attributed to human activities (deforestation, changes in water regimes, eutrophication, fragmentation of habitats, human-induced climate change), driven by the economic system [85]. Arguably, without their infrastructures and legal institutions, economic systems would not be so persistent and entrenched. This obduracy of technology, as observed in high-income industrialized country contexts, emerges at multiple levels and originates in multiple processes: in the mental frames of the minds of researchers, creators, designers, planners, engineers etc.; in the successive embedding of sociotechnical systems; and in the persistence of cultural traditions [80].

The kind of relationships technology establishes between humans and our environment changes in character and impacts as it becomes ubiquitous. As highlighted by Smith and Stirling [7], our current sociotechnical regimes have wide-ranging and long-term impacts on ecosystem resilience and may cause both incremental ecological changes and cascading effects. Previous historical sociotechnical regime shifts—such as the replacement of horse carts by cars, fuelwood by coal, and the ongoing attempted transition from fossil fuel-based energy systems to renewable energy sources—have often increased efficiency and driven growth within an economic context, but also been welcomed as solutions to environmental problems—polluting of the streets (horse carts replaced by cars), deforestation (fuelwood replaced by coal), or climate change (fossil fuel-based energy systems replaced by renewable energy sources)—and the environmental consequences have often been unintended and unforeseen.

We therefore suggest that sociotechnical dynamics not only underlie a lot of environmentally destructive practices, but are also likely to be decisive for the feasibility, relevance, and unintended consequences of strategies and management solutions proposed in response to place-based environmental problems. Understanding the dynamics of change across scales is a critical issue in STES research, hence, attempts at governance for the robustness and resilience of STES will need to investigate dynamics of scale at the interfaces that we currently understand the least.

5. Consequences of an STES Approach for Understanding Technology and for Framing

If one takes these previous motivations as a foundation for initiating more concrete research collaborations between SES and STS scholars, then a number of new questions arise: how do we organize collaborations? Around what research questions and topics? How do we integrate conceptually, using what frameworks, and what are the methodological consequences? Here, we will initiate this conversation, by asking ourselves how a shift from SES/STS to STES influences the framing of research. We can only hope to roughly describe some landmarks and to highlight some of the challenges, potential misunderstandings, and critical points for reflection as we move down this path.

5.1. A Dynamic Framing of Technology in Social-Ecological Systems

The four aspects above highlight that it is problematic to exclude technology from analyses of social-ecological relations, because technology is dynamic and mediates human–nature interactions, changes the scale of these interactions and works in ways that both create and solve problems, and because society is organized through and built upon technologies in basically all sectors. To this we should add the fact that policy makers include technological considerations in their agendas and make decisions regarding technologically related challenges; the temporal and spatial dynamics of the changes brought by the solutions implemented and the distribution of impacts and benefits among populations. Hence, if you want to address a complex problem at the society–nature interface and you do not explicitly consider the role of technology in your system, then you have a gap in your framework—a critical aspect is missing from the start. Furthermore, if technology is excluded from the problem formulation, from the conceptual framework, and from the analysis, then it will not be possible to arrive at conclusions or policy recommendations that engage technology at anything but a superficial level.

To avoid this problem, we argue for a framing that starts from symmetrical attention to the social, technological, and ecological dimensions, in the explorative phase. Depending on the phenomenon under study, some system elements and relations may come to fall in the background, or outside what is deemed feasible when setting the system boundaries of the study, but technology, or ecological systems should not be excluded, rendered passive, or 'black-boxed' from the start.

It is important to highlight that we are proposing a way of understanding technology and its interactions—rather than a framework—that can be useful in a variety of frameworks, studies, cases, scales, and levels. When exploring the phenomenon of interest, an STES framing (see Table 1) carefully investigates the types of relationships (ambivalent, transforming, embodying power, and relating to scale) constituted by technology at the interface of society–environment and the practices and consequences these relationships bring in time and space.

In comparison to previous literature, our approach shares many features with work in urban ecology that proposes a social-ecological-technical systems (SETS) framework [9]. We share the same insights around the importance of technology in the built environment, the difference being that we develop an in-depth conceptual basis for and content of such a framing, accounting for what technology is, how it is dynamic, what is does, and the kind of human–environment relationships it mediates. This is, we hope, helpful for SES scholars who are interested in collaborations but do not know how to conceptually approach technology. We thus go beyond identifying the intersection where social, ecological, and technical domains meet [9], and the discussion of similarities and difference between governance approaches in the respective fields [6], to specify the key aspects and framing consequences of our approach.

We believe an STES framing can enhance our knowledge regarding system dynamics, helping investigate interfaces and feedbacks that we do not understand very well. If we successfully map STES dynamics, then particularly interesting possibilities could open up for solution-oriented research. We envision that STES analyses will engage plural methods, plural problem formulations, plural pathways, and endpoints. Together, these provide a basis for assessing the possibility space for reconfiguration and redirection of human–environment relationships mediated through technology. Moving away from the exploitation and domination of one-way 'technical action'—that is, a relationship without reciprocity, responsibility, and accountability—demands that we render visible the social and material relationships that enable the displacement/relocation of negative impacts (the often mentioned 'externalities') so that these are carried by others. In particular, to effectively address questions in the realm of sustainable development, we need to close the analytical and professional gap between meaning and technology, to balance the efficiency criterion with more nuanced analysis of multiple factors and aspects, and shatter the illusion of transcendence by making visible the linkages, feedbacks, and systemic pressures.

Table 1. Summarizing the main technology aspects with corresponding main arguments for, and key features of an STES approach.

Technological Aspect	Main Arguments for including Technology in SES Analyses
Mediation	Technology mediates human–environment relationships Technology works at the interface and often is the interface Technology can be understood as means to execute purposes, working based on the harnessing of physical (and other) phenomena
Ambivalence	Technology is dynamic and sociotechnical systems are complex and emergent, imprinted with human values but cannot be reduced to these values. Technology produces ambiguous outcomes, is shaped by and reshapes society in a continuous process of becoming
Power and Agency	Technologies enhance and limit human capacities to act, but also transform these capacities and our interactions with the world. Technologies lend characteristic qualities to the kind of relationship established, reflecting underlying values and interests. Technologies are shaped by relationships of power and encode and embody the intentions of influential actors, but these intents are contested as other actors use, mold, and reshape technologies through their willful behaviors. Sociotechnical systems gain obduracy and render exercises of power more durable, but also give rise to systemic pressures that emerge from technology–technology interactions, technology–human interactions, and technology–nature interactions.
Scale	Technologies enable changes to the scalar relations of human–environment interactions in terms of quantities, space, and time. The kinds of relationships established change as we change scales and levels. Technologies enable centralized control, distanced action, and relocating effects to other places and times.
Key features of an STES approach	
An STES approach	*Starts* from a symmetric attention to society-technology-environment. *Approaches* the nexus as a complex system with dynamic and emergent qualities. *Reflects* carefully on the epistemological and political consequences of framing of research and works with mixed methods and multiple scales of observation. *Assumes* there are conceptual misunderstandings and frictions and spends considerable time at the early stages of research framing to identify these and learn each other's languages. *Explores* how technology contingently shapes the human–nature relationship and with what consequences; how emergent pressures in complex socio-technical-ecological systems are interlinked and; how intentional and unintentional technical mediation may result in ambiguous outcomes and feedbacks that displace/ relocate but do not remove negative consequences. *Seeks* to identify strategic interventions and ways of changing the kinds of relationships such that these embody values of reciprocity, care, and well-being for humans and non-humans alike.

5.2. Challenges for Bridging Between the Fields

We have provided reasons why research collaborations around STES are relevant, but previous literature has also highlighted some conceptual challenges and potential misunderstandings. These merit attention here. A first potential conflict has to do with the normative assumptions and priorities underlying the way problems are framed in research projects and collaborations, for example, relating to whether the current state of things is desirable or not, what exactly constitutes a problem, and what should change. These are often implicit in the favorite concepts and methods of particular fields. For example, the concept of resilience is central to SES, but for it to be useful in STES research, we need to ask: what should be resilient? Are we talking about resilience in the specific or general sense? The notion of 'resilience' takes on two meanings in SES literature. Specified resilience is defined as "the capacity of a system to continue to function despite exogenous shocks and uncertainty", also called 'robustness'. In addition, resilience theorists have also developed a broader notion of 'general resilience' that emphasizes "learning and the capacity to transform into a new system in response to change. Here, everything is in a state of flux." [8] (p. 137, 138). Smith and Stirling [7] are critical of the tendency among SES scholars to conflate the structure with the wished-for function, due to the way these are often closely related in SES. In earlier framings, resilience was defined as the ability to maintain system structure and function in light of both shocks and stresses in this wider environment [86]. In contrast, in the field of STS the problem is usually that existing sociotechnical structures—so called regimes—are resilient for the moment but unsustainable in the long-term. As Smith and Stirling [7] (p. 14) highlight, "Incumbent sociotechnical regimes are, by definition, structurally resilient. When regimes are no longer able to withstand shocks and stresses, they become destabilized". How to achieve destabilization of unsustainable but resilient structures is a core issue in sustainability transitions research.

This example illustrates that careful reflection on key concepts and the underlying assumptions is important to avoid misunderstandings, for good collaborations and the quality of the research. In practical terms, this requires that we invest much time for joint reflection at the early stages of new collaborations [87] and there is a pedagogical challenge at the heart of cross-discipline dialogue. However, making explicit underlying assumptions is important not only for good communication, but also because the process of framing in research is politically laden [11].

As Smith and Stirling [7] exemplify, there are political implications to framing a disturbance to an SES as a temporary shock or long-term stress. This is because policy responses to perceived short-term shocks can become impediments to necessary transformations in response to long-term stresses. The example given is of large-scale monoculture production of maize in the face of changing patterns of precipitation. If the focus is placed on maintaining the (specific resilience of) monoculture maize production, then efforts and a lot of resources will go into developing new kinds of maize that are resistant to drought, whereas a focus on (the desired function) food security may lead to a shift away from large-scale maize monoculture to other more diverse crop arrangements, such as intercropping or polycultures. In other words, investments in large-scale maize monoculture are likely to inhibit a more profound structural transition to other systems of food-production (for general resilience) in response to long-term stresses related to climate change [7,12].

To shift from SES/STS to STES brings the challenge of rethinking how and why we produce certain problem framings, choose our objects of study and make methodological choices. In particular, we foresee an interesting epistemological discussion around how to set system boundaries and what scales of observation to choose. We define observational scale as the temporal, spatial, or quantitative dimensions used by scientists to measure and study the world. As we have discussed at length elsewhere, the choice of scale mirrors the knowledge, culture, and priorities of the observer, it influences what can be seen and the conclusions made, and therefore scale itself requires scrutiny [88]. These are critical moments of the research process for two reasons: they have implications for the credibility of results and how our results are used in political processes that produce winners and losers, and they can bring out difficult tensions between conflicting ontological and epistemological positions. There are multiple ways of describing such differences—we may talk about a range of perspectives, from realist to constructivist [89], or positivist to relativist. Within each field, we find scholars who are trained in different traditions, who position themselves differently in relation to their study object. The tension shows in the question of how SES and STS scholars respectively understand the systems they study. We do not believe there is a true and a false epistemology, or that only one position is possible. Our contribution to this discussion is that, rather than taking a position of dismissal of the types of research questions asked by other researchers, such tensions reflect different underlying assumptions, but also different scales of knowledge [88]. To engage in bridging work—or digging tunnels, as suggested by a colleague (Cian O'Donovan, University of Sussex, UK)—the intermediate zone of tension is where we need to start. Interdisciplinary dialogues need to dig deep regarding how we understand scale to matter epistemologically, as moving across scales of observation often results in significant changes to what we (think we) see. For example, in ecological science, it is understood that structure and function are not absolute and change with the scale of observation [90]. What is function at one level of observation can be part of the structure at another level. As O'Neill and King [91] (p. 6) write: " . . . if you move far enough across scale, the dominant processes change. It is not just that things get bigger or smaller, but the phenomena themselves change. Unstable systems now seem stable. Bottom-up control turns into top-down control."

There is a tendency within all scientific communities to replace intense methodological discussions during the early years of community-building with a toolbox of taken-for-granted analytical frameworks and methods once the field has matured. In both SES and STS studies, there is already strong methodological awareness around the need for multi-scale analysis, mixing quantitative and qualitative methods, participatory and deliberative approaches to handle uncertainty and ambivalence, and for increasing the credibility of findings [29,92,93]. The methodological challenges cannot be solved or avoided, only handled well. This inspires careful reflection on the biases in and limitations of our methodological approaches, but more importantly, the friction that comes with mixed methods and data sets that do not align is a source of new insights, a space where new questions emerge—which is called triangulation for divergence [88].

A final challenge to highlight from previous literature is that, despite the priority given to policy-oriented analysis, engagement with stakeholders [43,50,94,95], and similarities in governance approaches [6,29,96–99], both fields still struggle to recognize the politics and conflicts inherent to governance processes. This critique is possibly more pronounced in the STS field [72,100,101]. Smith and Stirling [7] emphasize some insights on governance in the STS field that they suggest are equally relevant—and problematic—for SES research. For example, the field of transition management aims at steering processes of sociotechnical change through arenas where visionary actors participate in efforts to create new solutions. The management process involves problem structuring and goal envisioning, experiments, learning, adaptation, and institutionalization. The emphasis lies, however, on co-operation, collaboration, and consensus building, whereas conflict is downplayed [72]. But inviting a wider set of actors to the arena does not solve the questions: "Who governs? Whose system counts? Whose sustainability gets prioritized?" [7] (p. 17). Working on STES will not automatically provide answers to these questions. However, we suggest that by placing analytical focus on the kind of human–environment relationship that is there, and that we seek to achieve by our intervention, we need to ask ourselves and each other what worldview and ethics inform our priorities.

5.3. Counterarguments Against Research on STES

In the course of our reflections on STES we have found at least three counterarguments to the explicit integration of technology in SES. The first two call for redundancy, given the already interlinked character of society-technology-nature, while the third argument questions whether it is always a necessary requirement to include explicitly the technological dimension of our systems for our analyses to be fruitful. We present here these counterarguments, posed as questions and followed by our answers.

Why distinguish at all between society, technology and nature if they are components of the same complex systems? We prefer to talk about STES rather than complex systems because of how we understand the ontological foundation of STES conceptualizations. Collapsing them all into one big system is not fruitful analytically, given the significant differences between ecological processes and human practices and the distinctive nature of technology, irrespective of our cognitive abilities or analytical needs to draw or dissolve boundaries between society, technology, and nature. The point we are trying to make by defining STES here is that the SES and STS literatures share many insights but also contribute distinct and valuable perspectives that the other field would benefit from learning about, given their shared interest in addressing some of the most challenging and complex questions related to the concept and vision of sustainable development.

If technology is part of society, then isn't it already included in the 'social' of SES? The answer is that in principle it is possible, but much of the practice we have seen does not include such analysis. We agree that society and technology cannot be meaningfully separated. Society and technology are mutually constitutive, which is also what the concept of 'sociotechnical' systems signifies. However, SES analyses tend to ignore the sociotechnical character of society, and technologies and their functions are generally given little/no attention, or rendered passive. Furthermore, technology cannot be reduced to the social values imprinted upon it. The arguments around the four aspects of mediation, ambivalence, agency, and scale show that technology does something to these values, translates and transforms them into something different that is not just social. This is why SES would benefit from giving technology analytical attention, to the same degree as the interest given to the social and ecological dimensions of SES.

Finally, is it always necessary to include technology given that one cannot include everything in one's analysis? This is a key and legitimate question, given that not only technology is important, but there are also economic, cultural, and political aspects that deserve our attention. Indeed, we are not arguing for focusing on T in every social-ecological systems analysis, but for enabling frameworks that let us arrive at a decision on how much T should be included in our analyses, by thoughtfully examining possible consequences of its exclusion. It is not a goal in itself to be as inclusive and holistic as possible in our frameworks and analyses. One value of a good conceptual framework is to help us select our focus in order to achieve our analytical interests well. Let us be more specific and relate this consideration to systems theory. As we see it, systems thinking is based on an acknowledgement that our 'systems' are analytical constructions, and therefore by necessity are simplifications of complex phenomena and processes in the real world. We use them to help us make sense of the world and generate knowledge that is relevant, credible, and helpful in implementing solutions. How to conceptualize your framework is a matter of analytical interest and objectives, the type of questions you are asking, what is the normative foundation, and goal of your research.

So, returning to the arguments stemming from the interface and mediation aspects of technology for STES, what we suggest is to not forget about the central location of technology and to consciously reflect on its dynamic role in the causal relationships of interest when designing research. Considering technology becomes more important, in our view, as the phenomena studied transgress multiple organizational levels, extend across networks, and connect people and places over time and space. Energy and food production, degradation of land and water bodies, deforestation and pollution, all these phenomena provide for a richness of possible STES framings and research efforts.

6. Conclusions

In this article, we have argued for the importance of integrating the perspectives of social-ecological systems and sociotechnical systems in a new socio-technical-ecological systems (STES) approach, identifying a clear interface between the SES framework and work done in STS on sustainability transitions. We think integration and translation across these fields will lead to some qualitative change in the theoretical and methodological approaches of both fields. Like Redman and Miller [10], we think that a more pluralistic understanding of how social, technological, and ecological domains interact is necessary.

In particular, we contribute to bridging across disciplinary boundaries by providing arguments stemming from four aspects of technology—of ontological character—for why this shift in framing is important. Technology works as a mediator between us and the natural world. It produces ambivalent outcomes, transforms the exercise of power, and gives rise to systemic pressures, and changes the scale of our interaction with and impacts on the natural worlds. Together, these reasons amount to a coherent and dynamic approach to technology tailored for integration with SES studies.

Taking some first steps towards operationalization, we outline key features of an STES analytical approach, suggesting that technology, society, and ecology should be given symmetrical analytical attention at the explorative stage of framing research problems, questions, and scope (see also [52]). This is important because taking power seriously requires that one takes technology seriously. Also, excluding technology or environment from the problem formulation, conceptual framework, and the analysis precludes conclusions or policy recommendations that engage these at anything but a superficial level. The added value of shifting from SES to STES lies in a better understanding of system dynamics at some of the interfaces between sociotechnical systems and social-ecological systems that have so far received very limited attention. In this regard, work on STES opens up new research areas, and the identification of a wider range of risks, uncertainties, interactions, and feedbacks, together with thoughtful consideration regarding strategies for reflexive and adaptive governance and the associated challenges and politics, could increase the feasibility, reach, and relevance of nexus research. In light of the discussion, we conclude that the nature of the collaborations needed across the two fields goes beyond each field adding pieces together. As the next step, we suggest that interdisciplinary research teams start work on joint case studies and experiment with symmetrical STES framings to identify the ontological and epistemological frictions, and work towards joint research questions to be explored through multi-method and multi-scale investigations. Two types of case studies can complement one another. First, studies of historical systemic shifts connected to industrialization with accompanying changes in use of land and water ecosystems, materials, and energy resources can produce important conceptual and methodological insights. Second, innovation oriented transdisciplinary engagements with specific places, co-innovators, and change processes can provide important additional insights regarding the ethical and political aspects of STES research.

Ultimately, collaborating across the fields may increase our relevance in the policy domain and provide a critical voice that questions the technocratic and reductionist economistic narratives. This is much needed, given how the mainstream discourse on technology is still often apolitical or determinist—in the shape of either naïve technological optimism or gloomy dystopia. The professional separation between technical disciplines, the social sciences, and ecology is part of the problem we face, reducing the ability to challenge dominant discourses and practices. Joining forces can thus result in a more efficient critique of this paradigm, which has successfully upheld the illusion of transcendence—an illusion that is breaking down large scale ecological crisis and climate change.

Author Contributions: Conceptualization, H.A., I.R.-M., S.M. and O.M.; Methodology, H.A., I.R.-M., S.M. and O.M.; Investigation, H.A.; Writing—Original Draft Preparation, H.A.; Writing—Review & Editing, H.A., I.R.-M., S.M. and O.M.

Funding: This research received no external funding but the work has been made possible thanks to the following institutions: Helene Ahlborg and Sverker Molander gratefully acknowledges the financial support contributed by Chalmers University of Technology, Energy Area of Advance, and Ahlborg's current position is funded by the research agency Formas, grant nr. 2017-01012. Ilse Ruiz-Mercado acknowledges the support of El Consejo Nacional de Ciencia y Tecnología (Cátedra CONACYT). Omar Masera acknowledges the financial support provided by the projects PAPIIT-UNAM IT100818, and FSE-CONACYT-SENER 246911.

Acknowledgments: The article has benefitted much from discussions with colleagues providing suggestions and corrections during conferences and guest research sessions. We acknowledge the valuable discussions, comments and suggestions from Andy Stirling, Adrian Smith, Imogen Bellwood-Howard, Joni Karjalainen, Rocio Alvarez Tinoco, Tim Foxon, Fiona Marshall, Benjamin K. Sovacool, Kimberly Rogers, Bernhard Truffer and Sverker Jagers (who played a role in starting off our journey). Two anonymous reviewers provided helpful comments.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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