

# Integrating Social-Ecological Dynamics and Resilience into Energy Systems Research

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## Abstract

The ecological impact of energy production and consumption is often relegated in analytical accounts of the evolution of energy systems, where production and consumption patterns are often analysed as the interaction of social, economic and technological factors. Ecological and social-ecological dynamics are, we argue, critical in the context of imperatives for access to modern energy services that are inadequate for significant sections of the world's population. The ecological impacts of energy use are often analysed as a set of externalities, many of which are uncertain or unquantifiable, particularly if they stem from earth system change such as anthropogenic climate change. Here we outline the benefits from analysing energy systems as social-ecological systems. We review the extensive literature from ecology and resilience theories, and compare the analytical domains, major findings and emphasis of social-ecological systems with socio-technical transition research. We illustrate these differences with the example of the multi-scale impacts of biofuel expansion. We show that social-ecological systems research combines analysis of interactions with ecological systems and power relations between actors in energy systems, and has the potential to do so across production, distribution and consumption domains whilst illustrating the dynamics of such energy systems, identifying potential trade-offs and regime shifts.

## Keywords

Social-ecological systems; Resilience; Energy systems; Biofuels.

## 1. Introduction

Whilst discussing the underutilisation of social science related disciplines, methods, concepts, and topics in contemporary energy studies research (1), we argue that the integration of ecological dynamics are also not examined equally. There is an intrinsic link between current energy regimes, renewable and non-renewable natural resources, and global and place-specific environmental change. Energy production and consumption patterns are, therefore, not only determined by the interaction of social, economic and technological factors, but also by ecological dynamics. The importance of ecological dynamics within energy production and consumption are often relegated in analytical accounts of the evolution of energy systems. Such ecological impacts are often analysed as a set of energy externalities, many of which are uncertain or unquantifiable, particularly if they stem from whole earth system change such as driving anthropogenic climate change. The uncertainty around impacts explains the lack of integration into traditional analyses of energy systems and we suggest that this creates an opportunity for framing energy systems as inherent social-ecological systems that have inherent vulnerabilities, resilience and capacities for change.

There are still huge challenges for energy systems to achieving social, economic and environmental sustainability (2). The global energy system continues to be locked-in to fossil fuels and presents four main challenges to sustainability (3, 4):

1. The challenge to reduce greenhouse gas emissions from fossil fuels contributing to climate change at a global scale (with differentiated local impacts), and as the primary source of local air pollution with direct impacts on well-being and ecosystems;
2. The challenge of energy security through increasing demand and limited supply of fossil fuel products, and price uncertainties;
3. The challenge of pervasive subsidy of fossil fuels and the geopolitical dimensions of the carbon economy;
4. The challenge of universal access to energy services and energy poverty.

To take the example of energy poverty, 1.6 billion people lack access to electricity whilst 2.4 billion rely on biomass and other solid fuels (i.e. wood, charcoal, waste) for cooking (5, 6). This challenge is being tackled, for example, by international initiatives and domestic policy strategies that create pressure for the expansion of clean energy access in developing countries (such as the Global Alliance for Clean Cookstoves) (7). The challenge of universal access to non-biomass fuels has also promoted the use of liquid biofuels in the agricultural, industrial and residential energy sectors to allow a range of applications including off-grid electrification, household energy, small machinery power, irrigation pumping and food production equipment (7, 8). A reduction in the use of biomass for Total Primary Energy Supply has been shown to have highly significant benefits for rural and urban poor populations through reductions in acute respiratory infections in women and children (9). Similarly a reduction on biomass dependence affects land use, tree cover, and an increase in the proportion of agricultural residues returned to agricultural land (10). There are also time savings for women, who traditionally collect biomass fuels, but could benefit from increased income-earning activities, education, or leisure time. There are, therefore, demonstrable benefits to increasing universal access to modern energy sources, but also significant political economy dimensions that prevent access to energy for low income groups globally.

Transformations and opportunities for change in the production, distribution and consumption within energy systems all have links to multiple social and ecological processes. Whilst addressing these challenges requires integrated solutions with competing objectives, there are strong drivers for transformation to decarbonised systems that provide energy access to all. Whether change is introduced top down or grows from the bottom up, we argue that understanding the dynamics and the opportunities for progressive change will require models that explicitly incorporate social-ecological dynamics and the nature of resilience.

## **2. Bringing ecological resilience into energy analytics**

Resilience is a systematic property that refers to the magnitude of change a system can experience before shifting into an alternative state (11, 12). Whilst introduced in the field of ecology in the 1960s, in the last decade the concept of resilience has been taken up by social scientists to investigate non-equilibrium system dynamics in social-ecological systems (13). As a result, resilience has also been widely recognised as a policy goal in urban planning, development strategies, and the management of critical national infrastructure (14, 15). Social-ecological resilience has three components: the amount of disturbance a system can absorb and still remain in

the same state; the degree to which the system is capable of self-organisation; and the degree to which the system can build up and increase the capacity for learning and adaptation (16).

The combination of robustness, autonomy and learning signifies that a system is resilient if it can adapt to remain in the same state, but is also resilient if it has a high enough capacity to deliberately transform into new forms and configurations. In comparison, a system that undergoes a regime shift unintentionally due to a lack of adaptive capacity lacks resilience. Integrating these ideas of dynamics and intentionality is important when framing the behaviour of social-ecological systems.

Social-ecological systems are integrated systems in which humans are part of nature and therefore cultural, political, social, economic, ecological and technological components interact (17). The interacting components form a complex and dynamic entity, the analysis of which requires a holistic approach. The equal attention paid to the social and ecological components of a system, and the focus on the relationships between these components rather than their individual functions, is key within resilience theory (18). A social-ecological resilience framework is therefore able to illustrate the dynamics of such systems, identifying potential trade-offs and regime shifts.

There are diverse ecological dimensions of energy production and consumption. Much analysis of the costs of energy use focus on direct impacts on well-being such as on health, or their economic costs and presents such results in cost-effectiveness, cost-benefit or life cycle frameworks. The costs of fossil fuel based electricity generation, of hydro-power or biofuel alternatives, as well as of the energy dimension of consumption patterns, can all be compared using such analyses (19, 20). There are well-established critiques of economic valuation of environmental externalities (21, 22). They highlight how the meaningfulness of monetary valuation breaks down the further the externality is from market-type impacts. An economic cost of air pollution on labour productivity is unambiguous. By contrast, the economic cost of species extinction or the loss of visual landscape amenity, are less meaningful. Hence externalities associated with ecological decline in particular are much less consistent with economic values, not least in the intrinsic values of nature beyond the ethnocentric framing (23, 24).

In economic analysis of energy externalities, for example, impacts are often valued as loss of biological diversity or valuable habitat, valued in economic metrics through replacement cost or of the economic values of genetic material (25). But many ecological values are context and place specific and have wide ranges of attributed economic values. Such wide variation and analytical difficulties in attributing value in effect introduces uncertainty to such analysis. More fundamentally, however, the economic externality framing has significant limitations in incorporating dynamic and contextual dimensions of ecosystem responses to interventions. Ecological impacts are generally accounted as the externalities associated with habitat loss, changing land use, or pollution loading, costed as replacements for the ecosystem service, or by comparison of values lost through choice experiments to compare ecological loss with some other reference-good. But ecosystem stress has multiple routes to affect system resilience, through closing off future options, bringing ecosystems close to thresholds of regime shifts that may be effectively irreversible, and other non-linear effects (26).

Hence we argue that conceptualising energy systems through a resilience framework internalises the ecological variables that are often externalised in traditional analyses, by framing them as equally as important as the economic, technological and political factors. The benefits of a resilience framework will be outlined below, but in summary, such a framework allows a wider analysis of the

trade-offs between the elements listed above to be highlighted, providing greater information about potential changes in the system.

### 3. Systems: social, technical, and ecological

#### 3.1 Traditions, convergence and difference

If ecological dynamics are difficult to incorporate in standard energy analyses, we argue that more systems-oriented analysis presents opportunities to examine both the environmental and ecological dimensions as well as portraying more fully how energy 'fits' within society. There are two distinct and parallel systems analyses, based on different traditions. First, social-ecological systems research explicitly analyses the biological basis of ecosystems and their interaction with social processes including the exploitation and relationship to biological and other resources. A parallel tradition focuses on socio-technical systems as interactions between social practices and technological artefacts that influence each other. Analysis of such systems has commonly been utilised to address the acceptability, uptake and performance of technological innovations (27-30). To do so, analysis of socio-technical systems incorporates knowledge, markets, regulation, cultural meaning, infrastructure, maintenance networks and supply networks as well as artefacts and practices (31).

Both the socio-technical and the socio-ecological traditions use multi-scale perspectives, examining complex and dynamic systems (32-34). Both also refer to the idea of adaptability and transformability, and the importance of iterative learning and knowledge within the system to allow these processes (12, 28, 34). Various studies seek common ground between these fields (34-37): the commonalities between the two are clear. As emerging environmental and resource problems are framed as complex systems problems, integrative and interdisciplinary approaches are developed to address them. Berkes et al. (18:2) argue that resilience has a place in integrated sciences as "*sustainability implies maintaining the capacity of ecological systems to support social and economic systems*". By assuming change and explaining stability, rather than assuming stability and explaining change, resilience offers the required holistic method of analysing the dynamics of interrelations within complex social-ecological systems (18, 38). Socio-technical systems analysis also arose from a complex systems perspective, in response to the challenges of understanding complex technical systems embedded in social systems (39).

However, the distinct domains of socio-technical and social-ecological systems research reflect, according to Smith and Stirling (34), different objectives, views of progress, development, and framings of problems. Ecological systems research, for example has a definite spatial context and unit of analysis, while focus on socio-technical systems often do not have explicit spatial dimensions. While socio-technical systems are often normative in their explicit objectives of promoting transitions and transformations to more desirable and sustainable energy systems, social-ecological system analysis is more ambivalent concerning societal objectives and normative framings (40). The analytics of social-ecological resilience is neutral on the societal desirability of particular ecological states, while recognising that most observed trends in ecosystem change are detrimental to the provision of ecosystem services. Despite this foundation as an observational science, resilience is now widespread as a positive and normative goal of policy and practice (40).

Both research traditions recognise imperatives for transformational change. In social-ecological systems transformation involves fundamental alteration of society and the ecological system on which it depends. Some transformations are intentional, but the observed global transformations in

ecosystems demonstrate that most transformations are inadvertent and the consequences often hidden or unforeseen (41-43). The discussion around how to initiate transformation is increasing and focusing on the need for innovation to break self-reinforcing feedbacks which create resilient systems. For example, poverty traps are resilient structures that undermine the intended function system but are socially undesirable (44, 45). Technological regimes differ in their overall desirability depending on the temporal viewpoint as once an alternative is produced, the desirability of the previous socio-technical regime decreases (46).

Transformation is not, however, the first response to an undesirable system. Evidence from both socio-technical and social-ecological systems research shows the tendency for systems to use adaptive capacity to respond and maintain function. Many social and economic structures prevent transformations in energy systems, ranging from short-term vested interests to the cultural construction of comfort, risk and social practice (46-49). A critical frontier of research remains how to integrate research on social practice, political economy and social learning into transformations of energy systems.

### 3.2 Opportunities and examples

Among the major challenges for energy systems are those associated with the development of non-fossil fuel alternatives that both increase energy access and retain sustainability of the natural resource base. We argue that these new sources of energy production and consumption are best analysed in a systems framing that gives critical insights into thresholds, the distribution of benefits and risks, and the interaction with ecosystem dynamics. Hence in this section we illustrate such analysis and dilemmas for these emerging energy systems.

All energy production and consumption decisions involve trade-offs. These include, for example human health and ecological impacts, the use of land resources for new renewable energy technologies compared to alternative energy sources, and the benefits to energy consumers. Table 1 presents an overview of low-carbon energy systems, the technological and social dimensions and ecological dynamics. It identifies the potential trade-offs and vulnerabilities associated with emerging energy systems, such as between ecological stability and economic development objectives.

Table 1. Examples of social, technological and ecological dimensions of emerging energy production systems.

Energy system	Technological and social variables	Ecological variables	Examples of social-ecological trade-offs and vulnerabilities
<b>Renewable energy - wind</b> (50)	Energy potential, scalability, cost effectiveness, supply variability, distance to urban centres of consumption, aesthetics and technological acceptability.	Topography, habitat quality from associated infrastructure, wildlife mortality and disruption, energy potential.	Areas of maximum wind strength can be far from consumer populations, requiring costly transmission infrastructure, decreasing efficiency. Bird collisions are dependent on the spatial allocation of wind turbines.
<b>Renewable</b>	Energy potential,	Biodiversity, underwater	Construction of offshore

<b>energy – marine</b> (51)	scalability, cost effectiveness, distance to urban centres of consumption, aesthetics and technological acceptability, ownership and tenure.	noise, emission of electromagnetic fields, collision, sediment removal rates, suspension rates, biological oxygen demand (BOD).	developments causes physical disturbance to the local environment, with short and long term implications on biodiversity and water quality.
<b>Biofuel as fossil fuel substitutes</b> (52-54)	Energy balance, cost effectiveness, transport infrastructure, labour market implications.	Air and water pollution (N <sub>2</sub> O, CO <sub>2</sub> , CH <sub>4</sub> , fuel use), substitute land use, habitat quality, plant pathogens and landscape diversity.	Land use change to biofuel feedstocks can create a carbon debt and reduce access to those lands for prior users.
<b>Terrestrial carbon storage (REDD+)</b> (55)	Energy balance, leakage rates, land tenure implications and the distribution of rights to carbon, cost effectiveness, implications for forest product markets.	Air and water pollution (N <sub>2</sub> O, CO <sub>2</sub> , CH <sub>4</sub> , fuel use), substitute land use, habitat quality, plant pathogens and landscape diversity.	The transition from a conservation ethos to a utilitarian one simplifies nature and undermines socio-ecological resilience by underplaying ecological risks.

To take the dilemmas around biofuels as fossil fuel substitution in Table 1 as an example, it can be seen that this energy system has significant social and ecological dynamics. The impacts of land use change associated with biofuels impacts on ecological systems, through changing the demand for land and water, displacement of food production, and changing land access are significant. At the global scale, the expansion of biofuel production in the past decade can be detected in the demand for land and in commodity markets (52). Biofuel expansion is implicated in exacerbating food price spikes in 2007-08 and in 2010-11, along with drought, reduced global food reserves and speculation (56, 57). Whether biofuel expansion is the principal cause or not, these food price spikes have pushed consumers below the poverty line and have been a causal factor in so-called food riots and socio-political instability in many countries at those times (58, 59).

But how does biofuel production and consumption affect energy and social-ecological systems at other scales? We analysed sugarcane-ethanol expansion in Ethiopia via a resilience assessment (60) to highlight the trade-offs and impacts on resilience at multiple scales. This system of biofuel production and consumption, perhaps unusually, builds on existing sugarcane production, does not substitute for direct food production, and is intended to be consumed domestically through use in improved cook stove technology. Our resilience assessment used data to construct a conceptual model of both the production of sugar cane and bio-ethanol, through to its distribution and consumption in Addis Ababa. Hence the assessment incorporates resources, stakeholders, institutions and issues ranging from impacts on food security of land displacement through to indoor air pollution (53).

The resilience assessment focused on the expansion of specific, existing, sugar cane production areas. We described and analysed system dynamics, possible thresholds, and winners and losers within the system. Analysis of primary household surveys focused on food and energy systems, regional secondary ecological data was synthesised via a life-cycle assessment, and interviews with key stakeholders demonstrated some important and nuanced results. We show that the ethanol

production system at the current scale does not appear to have breached any significant ecological thresholds and conclude that most of the sub-systems, and actors within them, are resilient to biofuel expansion to date, with the significant exception of pastoralists displaced by land acquisition. Sugar cane production is labour intensive. Manual harvesting of sugar cane, as practiced in Ethiopia, in particular creates a large number of highly-prized jobs and allows a highly flexible method of field management that reduces fertiliser and pesticide use, reducing reliance on imported inputs, a potential limiting threshold. The resilience assessment therefore identified the balance of costs and benefits, winners and losers, within the social-ecological system.

While such analysis demonstrates potentials for sustainable production and the benefits of consumption of kerosene-substituting ethanol, Ethiopian policy plans for a significant expansion. Our analysis concludes that expansion of sugarcane estates in Ethiopia brings risks of crossing important ecological thresholds regarding water availability due to the increased demand and uncertainties regarding future supply. The planned expansion would also represent a large contribution to Ethiopia's national greenhouse gas emissions due to land use change and diffusive emissions from constructed reservoirs. In addition, the expansion is responsible for encroachment into a National Park, resulting in significant negative impacts on habitat loss. Ongoing expansion has significant social costs, most notably the loss of access for pastoralists to traditional lands, with major social dynamics of moving to sedentary agriculture and wage-labour economic activities. We conclude that such energy system change has multiple interactions and impacts in the social-ecological systems of land use, food security and household energy consumption, over multiple scales. While the current rate of ethanol production in Ethiopia does not involve significant risks of ecological shifts to undesirable states, the risks of approaching social, economic and ecological thresholds is magnified by scaling up production at the regional scale.

#### **4. Conclusions**

We argue that energy systems have significant implications for social-ecological resilience. Analysis that combines social, economic, ecological, political, and technological elements of energy systems identifies potential trade-offs and regime shifts. A focus on resilience highlights potential thresholds to be avoided or managed at multiple scales.

Emerging and expanding non-fossil fuel energy systems, partly motivated by the decarbonisation challenge, are throwing up new dynamics and challenges in ecological systems. Hence there is a significant need both for recognition of ecology within energy social science, and for the incorporation of cross-scale dynamics of how impacts ripple through social-ecological systems. The single most vociferous critique of social-ecological systems analysis from the social science relates to under-theorization and overlooking resource conflicts and the importance of power asymmetries (61, 62). Resilience studies commonly address the question 'the resilience of what to what' but not 'for whom' – whose needs are being met and the politics of their distribution (12, 40, 61, 63, 64). But we argue that progress can in fact be achieved by integrating political ecology to address power dynamics in social-ecological systems (40, 53, 62, 65). The incorporation of power dynamics allows the impacts of change in energy systems, for example technological innovation, to be addressed for all actors at multiple scales, allowing the balance of winners and losers to be made. This is key, whether examining top-down energy policy interventions or bottom-up innovations in energy technologies.

Trends in global environmental change highlight the necessity for transformation in wider socio-technical systems (66-68). Given the increasing interest in resilience of energy systems and

infrastructure by policymakers such analysis of social-ecological resilience has the prospect of more carefully elucidating the sustainability of local, national and global energy systems.

This discussion has highlighted three major research priorities for energy research and social science – two methodological and one regarding context. Firstly, research into how best to transform to a low-carbon energy system should not be done without a focus on the integration of the ecological dynamics within an energy system and we have argued that understanding the dynamics and the opportunities for progressive change will require models that explicitly incorporate social-ecological dynamics and the nature of resilience. Therefore, increased operationalization of a social-ecological systems framing will lead to a greater understanding of the trade-offs between elements of the system, cross-scale dynamics and impacts on resilience. Secondly, there needs to be a greater integration of social practice, political ecology and social learning within social-ecological framings to fully illustrate the spectrum of winners and losers across multiple scales. By analysing multiple nested scales using a resilience model and incorporating the power dynamics within these scales, the differentiated influences across multiple temporal and spatial scales by and on the actors within these scales are highlighted. Finally, ecological and socio-ecological dynamics are critical in the context of imperatives for access to modern energy services that are inadequate for significant sections of the world's population. Therefore, the third research priority must be applying these methods with an aim to illustrate how to increase access of sustainable modern energy to populations currently lacking any access. Modern energy access is a central tenet of achieving sustainable development aims and as such is the key to achieving the Millennium Development Goals.

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