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Towards a science of climate and energy choices

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The linked problems of energy sustainability and climate change are among the most complex and daunting facing humanity at the start of the twenty-first century. This joint *Nature Energy* and *Nature Climate Change* Collection illustrates how understanding and addressing these problems will require an integrated science of coupled human and natural systems; including technological systems, but also extending well beyond the domain of engineering or even economics. It demonstrates the value of replacing the stylized assumptions about human behaviour that are common in policy analysis, with ones based on data-driven science. We draw from and engage articles in the Collection to identify key contributions to understanding non-technological factors connecting economic activity and greenhouse gas emissions, describe a multi-dimensional space of human action on climate and energy issues, and illustrate key themes, dimensions and contributions towards fundamental understanding and informed decision making.

There is consensus in the scientific community and much of the policy community that human activities are bringing about deeply troubling changes in the Earth's ecosystems and in the biosphere itself. Some argue that the planet has entered a new geological era: the Anthropocene[1]. Anthropogenic climate change is arguably the most fundamental of environmental changes, in that human activities anywhere on Earth can affect planetary systems that produce physical, chemical, biological and social consequences at all geographic scales, anywhere on the planet, and stretching over centuries. Anthropogenic climate change is driven by many kinds of human activities, but the ones that have had the greatest effect over the past century involve the combustion of fossil fuels and the resulting atmospheric emissions, primarily of CO_2 (refs 2–4). Thus, energy use must be a critical focus of any effort to understand and control climate change, and it is central to the papers in this joint Collection.

Anthropogenic stress on the environment derives from the scale of human activities, the composition of what we consume, and the technologies and forms of social organization that we deploy in production and consumption[5,6]. These relationships are often encapsulated in the IPAT identity, which analyses the anthropogenic environmental impact (*I*) as the product of the size of the human population (*P*), the scale of human activity (*A*, typically measured as level of economic activity per capita) and a factor commonly called technology (*T*), but actually including, by the nature of an identity, anything — hardware, behavioural practices, forms of knowledge — that affects the degree of environmental impact per unit of economic activity[7]. The identity implies that controlling increased human stress on the environment could be accomplished through change in any of these driving forces. The Kaya identity, which is frequently used in discussions of climate change, is simply the IPAT identity with the *T* term divided into energy consumption per unit GDP and carbon emissions per unit of energy consumed[8].

Social science — broadly defined as the study of society and the way people behave[9] — has long been engaged in the study of *P*, *A*, and *T* in relation to various types of environmental impacts and has produced a rich and diverse literature[5,10]. The dynamics of population and of affluence are the central themes of major fields within the social sciences. Our focus here is on energy use and the consequent impacts on global climate. The most common research approach in this area has been to move from the IPAT identity to statistical models that estimate the elasticity of these drivers of impact — the amount of change in environmental stress per unit change in the driver. Other analyses examine the plasticity of the drivers — the amount that *P*, *A*, and *T* change as a function of other social or economic conditions, including deliberate interventions[11,12].

Efforts to reduce human stress on the environment have to take into account both elasticity and plasticity by trying to identify strategies that are feasible to implement and that will have substantial impact. At the same time, broader social and technological changes can shift plasticity, making things that were once hard to change more malleable. For example, subsidies for renewable energy can reduce the obstacle of up-front investment costs, making it easier for individuals and organizations to adopt these technologies. Many recent analyses suggest that the elasticity of human population size with regard to environmental stressors, including greenhouse gas (GHG) emissions, is about 1–1.5, a moderate but not inconsequential value[7,13]. At least since the 1960s the advantages of slower population growth have been understood, as have the factors that influence fertility, in particular women's empowerment, improved health care and access to effective contraception[14–18]. Affluence tends to have a higher elasticity than population[7,19], but as nearly every government promotes economic growth, it is not an attractive target for change unless, perhaps, the indicators of affluence are modified so as to separate measures of overall economic activity from the indicators of human well-being in order to focus on ways to increase the return on well-being of economic activity[20,21,22].

Of course, neither the elasticity nor the plasticity of the drivers of environmental stress is constant over time or across local and national contexts. Countries vary greatly in their ratios of CO_2 emissions to GDP, and many policies, for example, which promote energy efficiency and renewable energy development, are specifically intended to change this ratio[23]. Moreover, countries differ in their levels of integration into global production networks and supply chains, and into the global governance system of treaties and protocols. Thus countries are differentially engaged in the global environmental governance that comes both from public policy and from private sector environmental standards. Some countries

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Table 1 | A typology of social science energy and climate research.

Fundamental understanding	Immediate usefulness	
	No	Yes
Yes	Pure basic research (for example, history of energy use during the Renaissance).	Use-inspired basic research (for example, studies of the determinants of the adoption of energy efficient technologies).
No	Research that makes no contribution to knowledge; sponsored research or advocacy drawing inappropriately or selectively on science (for example, campaigns to discredit climate change science).	Purely applied research (for example, analysis to support more effective advertising campaigns for household renewable electricity systems).

The top-right cell is sometimes referred to as Pasteur's quadrant.

influence other countries by deploying their values and economic power[24–26]. In some cases this leads to convergent trajectories of economic development and environmental impact but in other cases these processes lead to sharply divergent paths of development with differing trajectories of environmental impact, including the offshoring of adverse environmental impacts to less powerful nations[27–31].

Social forces — such as power, culture, and institutional arrangements — shape the scale, content, techniques and trajectories of production, distribution, and the use of goods and services and their associated uses of energy. Thus an adequate analysis of the Anthropocene cannot proceed without substantial engagement in the social sciences. At the same time, the social sciences cannot make much progress working in isolation from the physical, ecological, health and engineering sciences. To advance the dialogue across disciplines, this joint Collection assesses the state of current knowledge that emerges primarily from the social sciences. Each paper constitutes a synthesis and points the way forward around some key problems. Taken together they provide a broad overview of the state of social science research on energy and climate change.

Most of the papers in this joint Collection are focused on climate and energy choices, and therefore on the social, cultural and political forces that shape the dynamics of energy production and use — the largest driver of climate change. That is, they focus on aspects of the *T* term in the IPAT identity other than technology. Of course, technological change in itself has great promise for addressing climate change. In an influential paper, Pacala and Socolow argued that increased adoption of existing technology could produce 'wedges' of CO_2 emissions reduction — so named because they represent contributions to reduced emissions that increase over time — that could potentially meet global energy needs for 50 years without doubling the preindustrial CO_2 concentration[32]. But for at least a decade since then, the plasticity of *T* has been less than hoped for, with the result that technological, policy and social change have not overcome the effects of growing population and affluence, and thus GHG emissions have not decreased.

Social science research is relevant to understanding why technological wedges have not materialized and how change in *T* — that is, in what we consume and how we produce what we consume, might be achieved. However, not all social science-based energy or climate research is immediately useful for these purposes. As Table 1 suggests, two questions can be asked of energy and climate research: does it have immediate practical implications, and does it contribute to fundamental knowledge? Some research does neither, and can even be regressive in the sense that it draws selectively on results in order to advance a certain policy agenda. Ideally, research programmes, including those described in the papers in this joint Collection, try to emphasize the upper right corner of Table 1 — what has been called Pasteur's quadrant[33]. The papers in this Collection tend toward Pasteur's quadrant, though they also include material from adjacent quadrants.

The papers in this Collection contribute to understanding by 'unpacking' *T*, and in particular by examining the great variety of non-technological factors affecting the connections between economic activity and emissions. These issues require an integrated scientific approach that engages the social sciences along with the natural sciences and engineering[34–41]. This has been called a science of coupled human and natural systems[42], or a second environmental science[43], and it is embodied in the concept of sustainability science[44]. This approach seeks to understand the human activities that alter environmental systems and the processes that drive them as well as processes that might reduce the environmental impacts of human activity while improving human well-being.

Social science insights on climate and energy

The papers in this joint Collection reflect the emergence of empirically based, data-driven science about climate and energy choices, drawing on diverse concepts spanning numerous social science fields. They provide greater nuance and realism than analyses that rely too much on attractive but empirically doubtful simplifying assumptions about energy choices. Some such assumptions are that the technologies that can alleviate the climate impact of human activities will be adopted when they pass a threshold of economic return to investment, that energy consumers' choices can be adequately modelled solely as a function of maximizing utility, and that decision makers have accurate information about the consequences of their choices and the ability to process that information unerringly. Energy analyses also often assume that governmental regulations will be implemented and followed fully once enacted, and that it is only through governmental action in the form of regulations and financial incentives that fossil fuel consumption can be controlled. Wise analysts recognize these assumptions as stylized and as overlooking important realities about human interactions with energy and environmental systems. Nevertheless, policymakers often treat results embodying these assumptions as adequate to guide their decisions. The papers in this joint Collection elaborate more realistic assumptions and the promising policy directions that they suggest.

Insights about human action that emerge from empirical and theoretical analysis, and demonstrate the value of the social sciences in addressing climate and energy issues, have a long history. They build on a tradition of social science research on energy that goes back at least to the nineteenth century, when grand theorists invoked energy as a key variable in understanding social structure and change[45]. The streams of research that lead to this joint Collection, however, are largely traceable to the 1970s, when the 'energy crises' that were articulated around the OPEC oil embargos stimulated new lines of analysis. Mazur and Rosa were among the first to note that energy consumption per capita and quality of life become 'decoupled' after a modest level of consumption is reached, and thus opened space for the analysis of energy efficiency as a social phenomenon[46]. This line of analysis has been linked to recent calls for a focus on well-being — rather than economic growth — as a metric of societal progress in analyses that assess the amount of damage done to the environment as a function of the amount of human well-being that a society generates — the environmental intensity of well-being[47–49]. Interdisciplinary research groups also soon began investigating the drivers of household energy use[50–53], initiating lines of research that continue today. By the 1990s, this work was closely linked with research on climate change mitigation, even as separate lines of scholarship examined vulnerability and adaptation to climate change[54,55].

Although the papers in this joint Collection might be categorized in various ways, we think it useful to imagine climate and energy choices in a space defined by three themes (risk and technology, nested hierarchies, and policy architecture) and three dimensions (the scale at which actions take place, the actors in various roles, and the processes occurring at multiple temporal scales). The papers occupy various parts of this space, and in doing so touch upon other relevant themes ranging from discourse and framing to governance and ideas about behaviour and identity.

Theme 1: Risk and emergent technology. Climate change makes evident the major risks associated with current energy systems. Social science research helps understand and explain differing perceptions of these risks and the differing support for policies to reduce them, both within and between national populations (ref. 56 and A. M. McCright *et al.*, manuscript in preparation). It can also help understand different interpretations and judgements about the feasibility, viability or desirability of particular technologies[57]. Such judgements can involve different interpretations of 'systemic risk' — hazards that are complex, uncertain, ambiguous, and which have the potential to reverberate throughout political, social, and economic dimensions[58,59]. For instance, as Table 2 shows[60], many energy systems alleviate some risks (or achieve social or economic advantages) only by presenting other risks (including social or economic costs). Oil has many uses but is prone to spills and generates GHG emissions; nuclear power is low-carbon but can have catastrophic accidents and presents a very challenging waste storage problem; renewable sources of electricity that emit no GHGs can present other dilemmas. In short, no energy system is free of potential adverse impacts, or free of risks.

Several contributions in this Collection address issues of risk perception and decision making, or analyse the risks of emergent energy technologies that could minimize the environmental degradation associated with conventional energy sources or even radically reorient energy markets. Wong-Parodi *et al.* focus on the decision-making process around emerging energy technologies and how different actors conceptualize the risks connected to them[61]. Others, in the tradition of past studies relating to risks associated with particular energy technologies, focus on technologies such as nuclear reactors and waste management[62] and commercial-scale sources of renewable electricity[63].

Theme 2: Nested hierarchies. Social science analysis can be difficult because social units are not neatly embedded in one another: individuals play multiple roles, have multiple affiliations with formal and informal organizations, and are fixed in multiple social networks. When units are neatly nested in one another — for example, individuals within households, within regional political units such as states or provinces, which are within nations — then well-developed methods exist for understanding the contextual effects, such as how national culture and institutions influence individual decision making[64]. When the nesting is more complex, such as with individuals holding simultaneous affiliations with local communities, organizations where they work, and social movements, then network analysis methods are required and the complexity of untangling multiple sources of norms, incentives and constraints increases greatly[65,66]. Indeed, units larger than the individual can be thought of as: (a) decision makers (a household decides to adopt solar photovoltaics, a corporation decides to build a wind farm, a national government decides to sign a treaty); (b) responders to network influences (an individual interacts with other household members, fellow workers, neighbours, and members of other informal social groups; corporations interact with suppliers, clients, competitors and governments); and (c) as contexts within which individuals make decisions (a household in a neighbourhood decides to by an electric car, a company within an industry decides to reduce its carbon footprint, an individual in a government agency decides to advocate for policies to reduce GHG emissions).

Analyses might ideally take account of all of these non-nested hierarchies and networks at once, but different streams of scholarship have focused on particular decision making units and roles, and on particular temporal scales of change. The most attention has probably been focused on individuals and households, and on their short- to mid-term changes in energy consumption[23], support for public policy[63,67], and participation in environmental decision making[68], undoubtedly because the research challenges are more tractable there. Still, network ties, embeddedness in larger structures, and influences across social levels are important determinants of choices[65]. Stern *et al.* discuss network effects on energy efficiency choices by organizations[23]. In advocating for more ethically informed decision making, Sovacool *et al.* propose involving multiple actors including consumers, jurists, and energy users in addition to investors and policymakers[62]. The typology of users presented by Schot *et al.* also shows[69] how a single person can occupy multiple overlapping roles and hierarchies.

The efforts of social movement groups to influence policies and corporate actions that in turn affect the choice sets available to energy consumers provide another example of multiple interacting levels of action[70]. For instance, the emerging 'divestment' movement seeks to influence public entities such as universities and religious organizations to eliminate fossil-fuel companies from their investment portfolios. The arguments for divestment range from the moral to the economic (for example, that these companies are bad investments because future policies will cause their energy assets to be 'stranded' in the ground and unavailable for economic return). The divestment movement seeks to send a message to fossil fuel companies that as a matter of corporate strategy and public image, they would be wise to diversify their offerings. Companies that offer their customers ways to meet their energy needs with lower CO_2 emissions make it easier for 'green' consumers to lower their carbon footprints. Such new linkages between consumers, firms, and communities of firms appear to be proliferating in environmental governance[71,72]. Of course, fossil fuel companies that seek to avoid stranding their assets often actively resist policies to reduce emissions, leading to a contested political terrain.

There are parallel issues for workers. For example, the expansion of residential solar photovoltaics (solar PV) may create more jobs than will be lost in the coal industry, but those new jobs will not be in the communities losing the old jobs. Similarly, the adoption of electric vehicles and nuclear power plants in Europe and North America might help make those societies more sustainable. However, they can impose social and environmental costs related to the mining of rare earth minerals and uranium in Africa and Asia and on the lands of native peoples in North America[73]. Such conflicts and trade-offs can at times undercut and even contravene the stated goals of energy and climate policies.

Theme 3: Policy and regulatory architecture. A third theme of these papers is that social science research can inform the design, monitoring, and evaluation of governance mechanisms. Non-regulatory government interventions to promote energy technologies generally fall into three broad classifications: supply-push mechanisms, often involving direct subsidies to producers; demand-pull mechanisms aimed at creating demand for them; and hybrid mechanisms which fall into both categories. Common examples of specific supply-push strategies include: (a) conducting basic and applied research

Table 2 | Eight energy system risk profiles.

Technology		Availability	Affordability	Resilience	Sustainability	Security
Oil	Pros	Historically in plentiful supply. Readily transported.	Historically inexpensive.	Many uses (such as electricity, transport).	Established supply networks.	Source of revenue for exporters.
	Cons	Majority of supply is in unstable nations. Risk of rapid depletion.	Future costs could present economic hardship.	Supply is controlled by unstable regimes. Supply routes are prone to risk.	Source of GHG emissions. Depletable. Risk of damaging spills.	Source of dependence and insecurity for importers.
Natural gas	Pros	Historically in plentiful supply. Readily transported.	Historically cheap source of peak load fuel.	Many uses (such as electricity, heating, cooking).	Established supply networks.	Source of revenue for exporters.
	Cons	Significant supply is in unstable nations. Rapid depletion.	Potentially expensive after low-cost reserves are depleted.	Some supplies controlled by unstable regimes. Supply routes are prone to risk.	Source of GHG emissions. Depletable.	Source of dependence and insecurity for importers.
Coal	Pros	Historically plentiful. Linked to transport infrastructure. Supplier diversity.	Historically cheapest source of base-load fuel.	Many uses (such as electricity, steel making). Easily stored.	Historically stable source of employment.	Source of revenue for exporters.
	Cons	Rapid depletion.	Mercury, CO_2 and other emissions produce severe hidden costs.	Supply route congestion.	Key threat to climate change. Source of major health problems.	Source of insecurity for importers.
Hydroelectric dams	Pros	Key domestic resource. Relatively predictable supply.	Cheapest historical source of renewable energy.	Largely subject to domestic control. Flexible renewable source.	Clean source of energy.	Easy to manage once established.
	Cons	Supply expansion has limits.	Environmental damages and decommissioning can represent hidden costs.	Undermined by drought, technical failures, and terrorist attacks.	Engenders environmental degradation and can entail the forced relocation of communities.	Can become targets during periods of social or military conflict.
Solar PV and wind electricity	Pros	Key domestic resource that any nation can exploit.	Many technologies are now commercially viable.	Different technologies suit different needs. Easy to scale up. Decentralized.	Clean source of energy. Among the highest ratio of jobs per kWh.	Decentralized generation improves system safety. Can minimize impact of fossil fuel price increases.
	Cons	Supply can be intermittent and unpredictable.	Intermittency poses hidden costs.	Can be undermined by environmental or climatic changes.	Requires integration with other systems.	Can be expensive and a source of voter dissent. Manufacture of solar cells dependent on rare earth minerals imports.
Nuclear power	Pros	Can help diversify energy portfolios.	Low historic operating costs after facilities have been paid off and/or subsidized.	Large, centralized plants are easy to secure.	Viewed as a low-carbon pathway to cheap energy in the future.	Nuclear technology spin offs can provide scientific benefits. Nuclear power is a status symbol.
	Cons	Requires high level of technical expertise.	Prone to cost overruns and long lead times.	Can undermine the electric grid when malfunctioning. Prone to terrorist attacks.	Presents major waste and safety challenges, as well as health risks.	Presents major waste management and safety challenges. Has troubling links with weapons proliferation. May require authoritarian or interventionist government regimes.

Continued

Table 2 | continued

Technology		Availability	Affordability	Resilience	Sustainability	Security
Biofuels	Pros	Most nations have some supply.	Potentially a good use of waste.	Can be produced by a variety of sources.	Meshes well with agrarian communities.	Can enhance agricultural development strategies, and minimize oil imports.
	Cons	Not enough to fully replace other fuels.	Food versus fuel controversy.	Requires continued expansion of land use to expand supply. Hard to ramp up.	Can require inputs such as pesticides and fertilizers.	Not an advanced use of land. Gives rise to deforestation and the resulting human and environmental insecurity.
Energy efficiency	Pros	Opportunities available everywhere.	Cheapest way to reduce carbon footprint.	Significantly reduces impact of conventional fuel price increases.	Gives rise to innovation and competitive advantage. One of the highest ratios of jobs per kWh.	Inexpensive to implement.
	Cons	Knowledge needed to exploit.	Can in some cases cause a rebound or takeback effect.	Solutions exhibit a progressively increasing cost profile.	Displaces jobs in traditional energy industries.	May encourage battles over standard setting.

and development on energy technologies; (b) building large test or prototype facilities; (c) government procurement of large amounts of an experimental technology; and (d) investor tax credits that spur innovation on a given technology. Common examples of demand-pull strategies include: (a) tax credits for the production or adoption of certain energy-using technologies; (b) rate-based incentives for favoured technologies; and (c) promoting technologies through training or information and awareness campaigns[74–76].

The papers in this volume expand upon such typologies and offer visions beyond the traditional regulatory and price-based mechanisms and beyond the notion that governance can be achieved only by the actions of governments[77]. A substantial literature demonstrates that consumers do not strictly adhere to the narrow rational actor model in making energy decisions — a diverse set of other factors including values beyond self-interest, inaccurate perceptions of the carbon footprints of consumer goods, and differential trust all play a role[23]. Non-economic motives for change in energy systems can be critically important influences on policy, such as when energy policies are responsive to notions of justice and fairness[62]. Influences beyond those typical in policy analysis offer important opportunities for action. For example, non-regulatory actions by government and private-sector entities to improve documentation of the carbon footprints of goods and services available in markets could enable consumers who want lower footprints to choose products that satisfy this desire. This possibility connects actors at different social levels and can affect choices with fairly long-term implications[78,79]. Marketing programmes that acknowledge the importance of trust in consumer decision making could prove much more effective than those that do not take into account how people assess new information, themes explored below in dimensions cutting across scales of action, actors' roles, and temporality. There is also research on ways that non-governmental actors sometimes perform important environmental governance functions independently of governments' actions, for example, by making binding agreements to reduce environmental footprints and establishing non-governmental regulatory standards and institutions[71,80].

Dimension 1: Scales of social action. Integrated energy analysis needs to examine the three themes of climate and energy choices: risk and emergent technology, nested hierarchies, and policy architecture in relation to the three dimensions of energy systems: scale, actors, and rates of change. Actions at levels of social organization from the individual and the household to communities and formal organizations, and on to national and international scales can all make meaningful contributions to mitigating climate change. Some papers in this joint Collection highlight energy choices at particular social scales: household and organizational energy consumption[23], community-level processes[63], and international governance[81]. Other papers present and discuss the analytical methods that can be applied at various levels to develop and validate empirical knowledge about energy choices and identify and test promising strategies for change[61,62,82,83].

Empirical investigation of energy choices at all social scales demonstrates the limitations of many simplifying assumptions often used in energy analysis. As the papers in this joint Collection show, approaches built on more realistic models of behaviour have the potential to achieve change in emissions that go beyond what can be achieved with the most commonly debated policies. Victor and Keohane's analysis of past experience with international agreements provides an example[81], as well as the call[83] from Geels *et al.* for integrated assessment modelling to be better blended with "practice-based action research". For instance, treaties among nations that place demands on all signatories are unlikely to be both achievable and strongly implementable, and therefore, have less practical potential for reducing carbon emissions than the aggregate of less-ambitious treaties involving fewer nations. Similarly, Stern *et al.* point out that financial incentives for household investments in energy-efficient technology have a tenfold variation in their uptake depending on implementation and point to a set of empirically derived principles for energy programme design that can combine incentives with other programme features to achieve greater plasticity in household energy decisions than incentives alone[23].

Dimension 2: Actors' roles. The multiple roles of social actors in energy systems are perhaps most easily seen at the level of individuals, who function not only as consumers making choices that affect their direct energy consumption, but also as members of organizations (firms, schools, churches and so forth) where they influence those organizations' energy choices[23]. In addition, individuals are also citizens, inventors, deliberators and legitmators[69] who may

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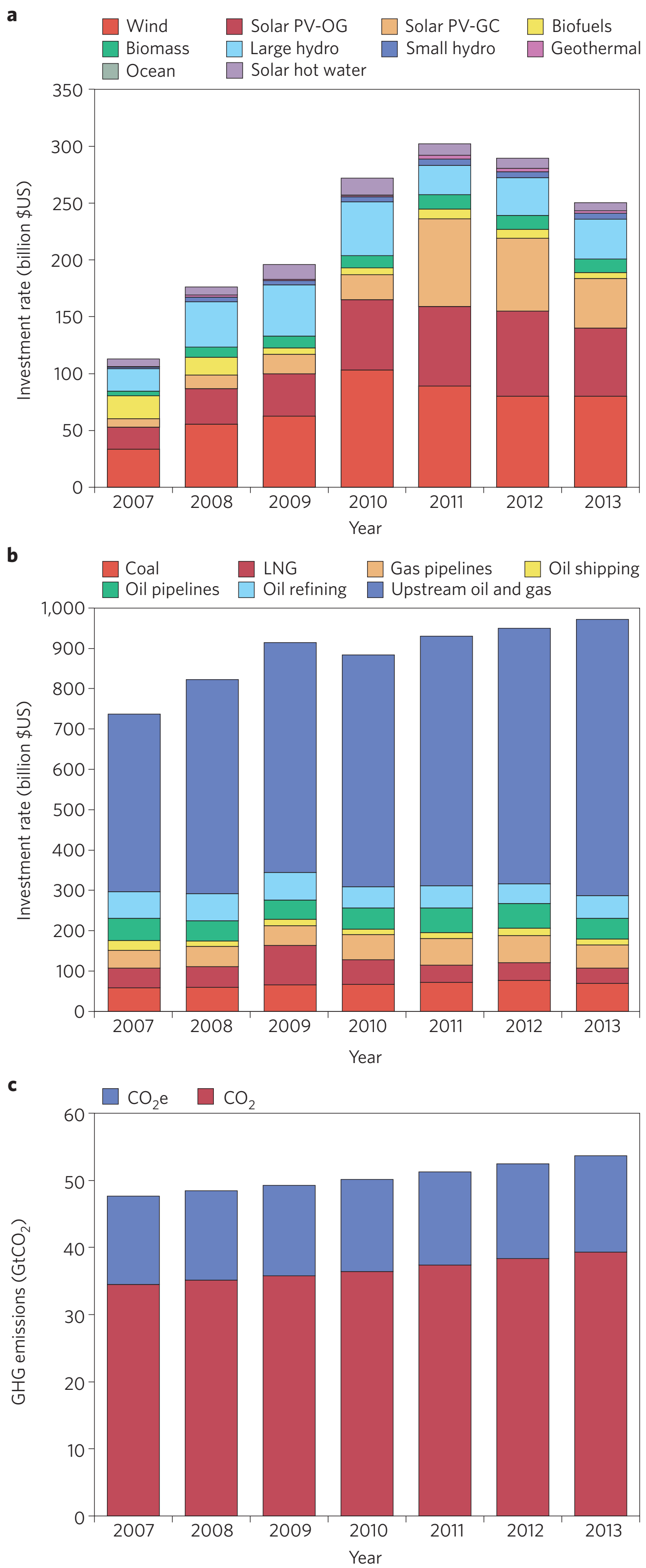

Figure 1 | Annual global investment rates in selected energy systems, and global GHG emissions, 2007–2013. a, Renewable energy investment rates. Biomass includes waste-to-energy, excludes off-grid fuelwood consumption. **b**, Fossil fuel investment rates. **c**, Global GHG emissions. The global GHG emissions figures assume IPCC's A1FI with growth allocations to countries based on ref. 87. Fossil fuel figures are from ref. 88. Renewable energy investment figures are from ref. 101. OG, off grid; GC, grid connected; LNG, liquefied natural gas.

express their views on public policy choices affecting energy production and consumption, and participate in social movement organizations that seek to influence the actions of governments or firms[84] or social justice movements calling for broader change[63].

Private sector organizations also act in multiple roles, they act as energy consumers, as producers of goods and services that shape the energy use by their customers, and as actors in policy systems[23,85]. Government agencies can have multiple roles: they are energy consumers; they can be energy producers; they supply goods, services and information to individuals and organizations; they conduct research on all aspects of energy; they are sources of regulations and other incentives and constraints on other actors in energy systems; and they participate in international assessment and decision fora[81].

Dimension 3: Pace of transition. Meaningful change can happen at various temporal scales. Over the short term, daily choices about energy usage (for example, choosing to use public transit versus a private car for a trip) can cumulate into important impacts. The mid-term scale of equipment replacement, such as household choices about which appliance or automobile to purchase or organizational choices about replacing energy-consuming equipment or the design of new buildings have substantial consequences. Long-term, roughly generational-scale choices and processes that affect what form new communities take, how transportation systems develop, what energy generation and transmission infrastructure is brought on line, and how social norms evolve have immense impact. Some papers in this joint Collection explicitly distinguish these temporal scales. Some focus on the potential for short- and mid-term changes in energy technology and its usage among households and organizations[23,62]. Others look at relatively longer-term changes in infrastructure, policy, and norms, including the dynamics of social networks[82] and shifting attitudes about local renewable energy developments[63]. Some consider the potential for change over even longer time frames of decades or even centuries, such as the challenges of managing long-term nuclear waste[62] or of analysing and informing large-scale low-carbon transitions[83] or global climate change agreements that often span generations[81].

The pace of widespread change in energy systems may be much slower than is often desired. Part of the reason is that renewable sources of energy have so far been slow to substitute for and displace fossil fuels[86]: major energy investments have not yet prioritized climate 'stabilization wedges'. The International Energy Agency has warned[87] that if "action to reduce CO_2 emissions is not taken before 2017, all the allowable CO_2 emissions [to keep global warming below 2 °C] would be locked-in by energy infrastructure existing at that time". Yet, globally, far more resources are still being devoted to new fossil fuel infrastructure development than to renewable energy and low-carbon infrastructure. As Fig. 1 shows, in 2013, investors directed about US$250 billion to all forms of renewable energy but sunk $950 billion into new coal, oil, and gas infrastructure. In the United States alone, oil and gas investment soared to $200 billion in 2013, amounting to 20% of total private fixed investment. This matched the volume of investment in home building, a first in the country's history[88]. Globally, investment in fossil fuel initiatives tripled in real terms from 2000 to 2013[89]. The bottom panel of Fig. 1 shows continuing increases in total GHG emissions over much of this period. Investment in both renewable and fossil energy is driven in substantial degree by costs and energy prices. Technological improvements are likely to drive down the costs of renewables more than they will fossil fuels. However, between 2013 and 2015 (the latest point for which data are available) the annual mean price of a barrel of oil declined from above US$100 to about $50, reducing the incentive to invest in alternatives.

It is critical, though analytically difficult, to consider the relationships that drive change at longer time scales, in addition to the short- and mid-term processes that have been most frequently examined[90].

An obvious example is the effect on future carbon emissions of the development paths taken by lower-income countries. A substantial literature shows that human well-being can increase without concomitant increases in energy consumption or environmental impact once a modest threshold of consumption is reached, and evokes important long-term questions. How can these countries move to higher levels of well-being while keeping emission low? Will new communities be constructed to be less dependent on motorized transport than older ones were? Will they be designed for linkage to locally available renewable energy sources? Where can the plasticity be found that would favour change from past practices in development?

Conclusions and policy insights

Social science and integrated research on climate and energy choices supports at least four high-level conclusions. Perhaps the most fundamental is the need to supplement analytical models based on simple assumptions (such as that of 'rational' economic choice with complete information) with assumptions based on empirical analysis of the phenomena of concern. Intellectually attractive but inaccurate simple assumptions are unlikely to yield the level of understanding needed to speed transitions to sustainable energy systems that meet reasonable targets for limiting climate change. Thus, in designing policies and programmes it is critical to realize that people and organizations do not use all available information and are strongly influenced by information that is readily available and comes from trusted sources. A step towards more nuanced policy design in this respect can be found in a recent Executive Order by US President Barack Obama[91]. In the consideration of energy systems, it is also important to recognize that judgements about risk have both objective and subjective elements and that adopting any energy system normally implies trading off some elements of security or sustainability with others. In making risk judgements, it is important for both energy consumers and energy researchers to become more informed and self-reflexive about their choices and underlying assumptions, so that they can better recognize their own biases, seek data-driven answers rather than those based on opinion or conjecture, and carefully differentiate assertions based on facts from those grounded in values[92,93]. The simple presumption that risk can be analysed from a single perspective fails to take into account that risk decisions intrinsically include judgemental elements and that affected people's judgements vary[61].

Second, addressing the challenges of energy sustainability and climate change requires analyses of human actions and the potential for change organized around issues in the space identified above, rather than by disciplines[94]. Disciplines can contribute, but their research efforts need to be guided primarily by (and organized around) problems rather than only by building and testing disciplinary theories. Integrated, cross-disciplinary and mission-oriented research is needed; a useful by-product is likely to be the creation of new interdisciplinary fields[36,38,40,41,54,95].

Third, available research makes clear that the effects of interventions are context-specific. Many energy choices depend on very specific aspects of particular role situations: the most obvious examples are energy retrofits and PV installations in buildings: every building is unique in its structure, equipment, orientation to the sun, and shading. Interventions such as regulations, prices, and other incentives may have non-obvious but important variations, as already noted[70]. For this reason, many kinds of interventions need to be somewhat individualized. Research can identify the key barriers that usually stand in the way of desired actions and guide a case by case diagnosis of the impediments that are especially important for specific choices. Contextual specificity makes energy users highly heterogeneous[69], the implication being that as in many other domains of human activity, empirical analysis of human interactions in energy and climate systems is unlikely to yield universal laws. Thus, in applying research findings, it is crucial to consider contexts and the multiple roles played by individuals, organizations and social institutions. The implications of research findings will probably vary across contexts and time scales. Consequently, what may appear as a general finding might increase or decrease in importance when extended to other contexts. Theories of context for climate and energy choices are at an early stage of development. Some contributions propose design principles for interventions that have fairly high generality but must be validated and refined empirically for particular choice contexts[96–98].

Fourth, if one accepts the need for more a rigorous, interdisciplinary, context-sensitive science of energy and climate choices, then funding and R&D strategies need to change. For example it has been estimated that in the United States research spending on topics related to energy efficiency and the behaviour of users was 1/35th of the research expenditures directed at hardware and building technology[99]. This bias towards supply-side technology obfuscates that it is often broader social, political, economic, organizational or cultural concerns that determine whether cleaner energy systems diffuse or energy and climate policies are effective. Current energy and climate challenges inextricably link the social with the technical. Many opportunities to examine those connections have been outlined elsewhere[3,41,54,94,100]; to pursue them, more attention and more funding must be allocated to social science analysis.

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Competing financial interests

The authors declare no competing financial interests.