Considering only first-order effects? How simplifications lead to unrealistic technology optimism in climate change mitigation

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ABSTRACT

This article challenges the notion that energy efficiency and ‘clean’ energy technologies can deliver sufficient degrees of climate change mitigation. By six arguments not widely recognized in the climate policy arena, we argue that unrealistic technology optimism exists in current climate change mitigation assessments, and, consequently, world energy and climate policy. The overarching theme of the arguments is that incomplete knowledge of indirect effects, and neglect of interactions between parts of physical and social sub-systems, systematically leads to overly optimistic assessments. Society must likely seek deeper changes in social and economic structures to preserve the climatic conditions to which the human civilization is adapted. We call for priority to be given to research evaluating aspects of mitigation in a broad, system-wide perspective.

Keywords: Sustainable development, climate policy, limits to growth.

1 Introduction

An underlying premise of world energy and climate policy is that energy efficiency increases and ‘clean’ energy technologies will, with appropriate policy support in place, be capable of delivering degrees of climate change mitigation consistent with the target of limiting global warming to 2° C above pre-industrial levels. Consequently, world policy to mitigate climate change remains somewhat superficial; underlying driving forces of the problem, that is – more resource intensive lifestyles and larger populations (Hertwich and Peters, 2009; UNEP, 2010a) – remain largely unchallenged, and fundamental changes in economic structures are hardly being put on the agenda.

Policy-supporting reports published by the International Energy Agency (IEA, 2010a, b) and the Intergovernmental Panel on Climate Change (IPCC, 2007) are commonly perceived to demonstrate the ability of technological solutions to deliver formidable degrees of climate change mitigation under scenarios of continued strong growth in the world economy. However, one insight which is too often overlooked in the debate is that the engineering-economic models behind studies such as IEA (2010a, b) rest on simplifications of complex and interacting physical and social systems, as well as intentionally optimistic assumption for the mitigation scenarios. In essence, what the engineering-economic models produce are extrapolations of first-order effect estimates under assumptions of well-functioning markets, neglecting linkages between climate change and other environmental pressures, and indirect effects of mitigation measures. By indirect effects we mean all effects of an action other than the action's targeted effect. Hofstetter and colleagues (2002) explain the notion of indirect effects by means of an allegory of ripples in a pond: Dropping an object into the pond (metaphorically: implementing a mitigation measure) sends out patterns of ripples, where the water height symbolizes environmental effects and the patterns of ripples the spread of effects through economies. The water height is immediately reduced at the point where the object hits the water surface (that is, the measure is successful in achieving the targeted effect), but high(er) water levels may be found anywhere from the inner to the outermost ripples.

In this article, we highlight some of the simplifying assumptions in current energy and climate change mitigation scenarios, as exemplified by IEA (2010a, b), and present a part of the case that it is premature to draw conclusions on the adequacy of technological solutions on the basis of such model results. Further, we argue that current, largely reductionist approaches to impact and mitigation assessments, where interacting problems and solutions tend to be assessed in isolation or with too narrow system boundaries, may lead to underestimation of environmental impacts on the one hand and are likely to cause overestimation of our ability to mitigate climate change on the other hand. As a result, mitigation assessments are the basis of unfounded technology optimism in world energy and climate policy. At the outset, however, it is important clarify that our critique does not concern the development of impact and mitigation assessments under simplifying assumptions as such. Rather, the critique targets the specific *interpretation* of contemporary assessments that, in the words of Ausubel (1996), 'technology can spare the earth' and the neglect of results that point in a different direction.

The next section introduces the challenge of achieving sustainability. In section 3, we challenge the premises for world energy and climate policy by six arguments which, in our view, have not been sufficiently acknowledged in the climate policy arena. The overarching theme is that incomplete knowledge of 'ripple' effects, and neglect of interactions between physical and social sub-systems, systematically leads to overly optimistic assessments. Section 4 concludes.

2 Background: the challenge of sustainability

According to current mainstream climate models, cumulative global carbon dioxide (CO_2) emitted by fossil fuel-burning, cement production, and land use in 2000-2049 should not exceed 1000 gigatonnes (Gt) if we are to have 75% confidence in reaching the 2° C target (Meinshausen et al., 2009). With 321 Gt already emitted in 2000-2009, we are left with a remaining budget of 679 Gt for 2010-2049. Negative growth occurred in 2009 due to the financial upheaval and slowdown of the global economy, but positive emission growth is expected to return as economic growth is re-established (Friedlingstein et al., 2010). Thus, at the onset of the second decade of 2000-49, we have not only emitted disproportionally high quantities of CO_2, but face continued growth in emissions. Moreover, national emissions-reduction pledges submitted under the Copenhagen Accord (UNFCCC, 2009) are far from sufficient to reach the 2° C target, even under the optimistic assumptions that countries will meet the ambitious ends of their pledges and refrain from exploiting loopholes in the regulatory framework (Rogelj et al., 2010; UNEP, 2010b). Also, recent observations give rise to concerns that climate change is occurring more rapidly than expected (Richardson et al., 2009), and there is a real danger that the neglect of long-term feedback effects in mainstream climate models lead to significant underestimation. Even by aiming for less than 2° C warming, there is a risk of irreversible and abrupt changes in climate (Hansen et al., 2008; Rockström et al., 2009).

In addition to climate change, an array of global environmental problems requires attention of policy makers. As an example, loss of biodiversity poses serious threats to life-supporting ecosystem services. The current species extinction rate is estimated to be 100-1000 times greater than the natural background rate (MEA, 2005; Rockström et al., 2009). One recent study finds that most indicators of biodiversity are in decline with no significant reductions in the rate of decline, whereas pressures on biodiversity are increasing (Butchart et al., 2010). Reviewing existing assessments of environmental impacts and pressures, the International Panel for Sustainable Resource Management highlights the following pressures as prioritized (UNEP, 2010a): Habitat change, greenhouse gas (GHG) emissions, over-fertilizing with phosphorus and nitrogen, pollution causing human and ecotoxic effects, depletion of abiotic resources (fossil energy carriers and metals), and depletion of biotic resources (in particular, fish and wood). Rockström and colleagues (2009) suggest nine indicators for evaluating the state of Earth systems. Of these, three indicator values (climate change, loss of biodiversity, and interference with nitrogen cycle) already transgress levels that can be regarded as ‘safe’, and four indicator values (global freshwater use, land use change, ocean acidification, and interference with phosphorus cycle) may soon be exceeding their safe levels. The remaining two indicators (atmospheric aerosol loading and chemical pollution) are yet to be determined (Rockström et al., 2009). As is further discussed in the following chapter, it is often not meaningful to view climate change and its mitigation in isolation from other sustainability issues. It is important that sustainability in the broad sense is adequately considered in climate change mitigation.

3 Six issues not sufficiently addressed in the climate policy arena

In the following subsections, we provide six reasons why contemporary climate change mitigation assessments are, in the general case, likely to be overly optimistic. While these six reasons represent problems that are not necessarily independent, they are discussed separately for the sake of clarity (Sections 3.1-3.6).

3.1 Transitioning to ‘clean’ energy supply will in itself cause climate impacts

The absence of fossil fuel combustion in the operating phase of energy converters (e.g. photovoltaic solar cells, biomass-fueled motor vehicles) does not imply zero greenhouse gas (GHG) emissions. This is because emissions occur in a network of operations necessary to support the energy converting process, such as manufacturing of solar cells or production of fertilizers to grow biofuel crops. Similarly, employment of carbon capture technologies in fossil fuel power stations does not remedy upstream emissions in the fuel-chain, which will rather increase due to lowered power plant efficiency.

The method of life cycle assessment (LCA) is the preferred method for quantifying and assessing environmental impacts generated throughout a product’s life cycle. Surveying a number of LCA studies of proposed solutions to climate change, Jacobson (2009) finds that power generation technologies cause life cycle GHG emissions of 2.8-7.4 g CO_2e/kWh (wind power), 8.5-11.3 g/kWh (concentrated solar), 9-70 g/kWh (nuclear), 14 g/kWh (tidal), 15.1-55 g/kWh (geothermal), 17-22 g/kWh (hydro), 19-59 g/kWh (solar photovoltaic), and 21.7 g/kWh (wave). Another study estimates 180-220 g/kWh and 140-160 g/kWh, respectively, for coal and natural gas power generation systems with carbon capture and storage (CCS), which compares with around 1000 g/kWh and 580 g/kWh for world average coal and natural gas power without CCS (Singh et al., 2011). Judging from these findings, non-fossil power generation technologies are far superior to fossil-fueled power stations; employment of CCS produces substantial GHG emissions savings, though the life cycle reduction is significantly lower than the capture ratio (capturing 90% of the carbon from coal power yields 74-78% reduction in life cycle GHG in Singh et al., 2011), and life cycle GHG emissions from fossil power with CCS exceed those of non-fossil technologies with up to one order of magnitude.

While the employment of LCA methodology is essential for making fair and consistent comparisons across technologies, it is important to recognize limitations to current LCA studies. First, conventional LCA methodology is known to suffer from systematic underestimation of impacts due to incomplete coverage of product systems: There is a limit to how many activities can be described in a bottom-up approach, hence unwanted exclusion of activities from the system of analysis will always be the case. There is no agreed upon methodology for quantifying the truncation bias of conventional LCA, and the results of existing inquiries are not uniform. Nevertheless, in all studies surveyed by Majeau-Bettez et al. (in preparation), it is found that conventional LCA misses out on 30% or more of total environmental impacts. Potentially, the problem of underestimation can be avoided by utilizing so-called hybrid LCA techniques, where economic input-output data is used to estimate missing inventories, and thereby complete the system (Suh et al., 2004).

Second, conventional LCA is dominated by *ceteris paribus* assumptions; it does not account for changes in the background economy in the case of widespread adoption of the product under study. A transition to de-carbonized energy supply will cause emissions in the background economy that are typically neglected in LCAs. For example, massive expansions of wind power necessitates updates in electricity infrastructure and/or energy storage technologies, and will, due to the fluctuating nature of wind power, lead to altered operation of hydro and thermal power plants. Additional CO_2 emissions of fossil-fired power plants caused by high wind power penetration have been estimated to 18-70 g per kWh electricity from wind (Pehnt et al., 2008). The additional emissions result solely from an increased need to operate thermal power stations at (sub-optimal) part-load in order to accommodate the fluctuating inputs of wind power (Pehnt et al., 2008). It needs to be emphasized, though, that such results depend heavily on the assumed characteristics of background energy systems.

Third, conventional LCA has its domain in assessing the impacts associated with the delivery of one (small) reference unit, but falls short of addressing the magnitudes of aggregated impacts. The aggregated impacts caused by adoption of energy solutions depend, among other things, on the pace of deployment, the temporal distribution of emissions, and replacement of existing systems at the end-of-life – factors that are not incorporated in conventional LCA. One study estimates GHG emissions brought about by a large-scale adoption of wind power to cover 22% of the world's electricity demand in 2050 to 3 Gt CO_2e (Arvesen and Hertwich, in preparation). Notwithstanding the important simplifying assumptions of this study (e.g., the calculation takes into account cleaner electricity mix in manufacturing with time, but not other changes in the background economy), it may serve as a first indication of the magnitude of aggregate life cycle emissions caused by global deployment of wind power.

It is not known what will be the global life cycle climate impacts caused by transitioning to energy solutions perceived to be 'clean'. It can be hypothesized, however, that the sum of all impacts is too large to be neglected.

3.2 Realized net climate change mitigation from energy efficiency is unlikely to live up to its expectations

Energy efficiency measures are essential in typically foreseen paths to climate stabilization (IEA, 2010a, b; IPCC, 2007; Pacala and Socolow, 2004). However, the true costs and benefits of energy efficiency are complicated and opaque, due to a number of socio-technical interactions manifesting themselves in two apparent paradoxical issues. The first issue, dealt with in Section 3.2.1, is linked with the fact that literature suggests that substantial amounts of energy can be saved at negative costs (IPCC, 2007; McKinsey 2009). This prompts the question that if there is a profit in reducing emissions, why does it not happen? The second issue, and the topic of Section 3.2.2, is the postulation and observation that through higher-order effects, energy efficiency gains may stimulate more energy consumption.

3.2.1 Negative costs

In essence, the occurrence of negative costs in mitigation assessments stems from two principle factors: *i*) market failures hindering the implementation of energy efficiency measures in real markets ('market failure factors'); and *ii*) discrepancies between what energy analysts assume to be optimal behavior and what is truly optimal from the point of view of individual end-users ('non-market failure factors'). Market failure factors include incomplete information, misplaced incentives and transaction costs. Two examples of non-market failure factors are high discount rates in the face of the irreversible nature of investments and uncertainty about future energy prices, and qualitative properties that favor conventional technologies over more efficient ones (Jaffe and Stavins, 1994; Linares and Labandeira, 2010).

Modeling results based on the utilization of negative-cost energy efficiency measures assumes that market failures and non-market failure factors can be easily overcome by climate policy. True, if, for example, policy measures such as information campaigns and appliance labels can create fully informed consumers or regulation removes inefficient alternatives, costs of gathering information will become zero once a successful new policy is in place. However, as long as conditions with incomplete information prevail, the costs are indeed 'real' in the sense that they must be borne – *de facto* hampering new investments. Misplaced incentives (landlord-tenant or principal-agent issues) and uncertainty in future energy (and carbon) prices are also likely to persist. Likewise, due to heterogeneity among end-users (Jaffe and Stavins, 1994; Linares and Labandeira, 2010), individual end-users may be faced with costs that are indeed 'real' to them, even if corresponding costs do not exist for average user types modeled by energy analysts. While policies to utilize the tremendous energy efficiency potential are desirable, assessments that count on the easy utilization of full technical energy efficiency potential are overly optimistic.

3.2.2 Rebound effects

Rebound effects come into play when increased efficiency leads to reduced costs. On a micro-level, increased energy efficiency will reduce the price of an energy service, and thereby: *i)* may create more demand for the energy service; and/or *ii)* may increase income available for general consumption. This applies to consumers and producers alike. On the macro-level, increased efficiency in the production and use of energy will result in a multitude of supply and demand adjustments occurring over time in a path-dependent development (Roehrl and Riahi, 2000). Because gains in energy efficiency favors energy over other factors of production (e.g., labor), and because efficiency contributes positively to overall economic productivity, the combined impact of the adjustments in supply and demand will be more energy consumption. The total economy-wide rebound effect is the sum of all micro- and macro-level effects (Hertwich, 2005; Sorrell, 2007; Jenkins et al., 2011).

The main arguments to be made here are that economy-wide rebound effects are likely too large to be neglected, and furthermore, that rebound effects are underappreciated in contemporary climate change mitigation assessments. Influential reports providing policy guidance on climate change mitigation (e.g., IEA (2010a, b), McKinsey (2009)) take little or no regard of rebound effects; thus, the net gains of energy efficiency measures are likely systematically overrated in such studies. We substantiate this position by briefly summarizing the current state of knowledge on rebound effects.

Empirical estimates of 'direct rebound effects', understood here as the increase in consumption of an energy service due to an efficiency-induced price drop of acquiring that service, typically fall within a range of 10-30% of expected gains for consumer end-uses in developed countries (Greening et al., 2000; Sorrell et al., 2009). Owing to the higher price elasticities, larger direct rebound effects can be expected for developing countries – a limited amount of empirical evidence suggests 40-80% (Sorrell 2007; Jenkins et al., 2011).

Macro-level rebound effects are more difficult to ascertain empirically and model-based estimates vary widely. Proponents of large economy-wide rebound effects ('backfire') have historically relied on theoretical arguments and more indirect sources of evidence to support their case (Sorrell, 2009). Modeling attempts to quantify economy-wide rebound exist, but the methodologies are subject to criticism and the evidence remains inconclusive (compare, for example, the different positions of Schipper and Grubb, 2000 and Jenkins et al., 2011; summaries are provided by Sorrell, 2007, 2009).

Macro-level rebound effects can be linked to the bigger question of what is driving economic growth: If it is so that energy is a major driver for economic growth, this strengthens the argument for large rebound effects (Sorrell, 2009). According to conventional growth theories, energy can only play a minor role in generating economic growth, since the costs of energy are low compared to capital and labor costs. This view is contested by the analyses of e.g. Kümmel et al. (2010) and Warr and Ayres (2010), which indicate that capital, labor, and energy are in fact interdependent inputs, and that high-quality energy is a major driver for economic growth (Sorrell, 2009; Madlener and Alcott, 2009). Sorrel (2009) acknowledges that the identified relationships between high-quality energy and economic activity do not represent sufficient evidence to conclude that causality runs from energy to growth, but argues that the observations are consistent with theoretical arguments offered earlier.

Returning to our main argument, we see considerable grounds for concern that due to rebound effects, energy efficiency strategies will fail to live up to expectations as a contributor to climate change mitigation. There is universal agreement in the rebound literature that some rebound effect exists; thus, at the least, net gains of energy efficiency are smaller than suggested by simple engineering estimates. Furthermore, while the exact magnitude of economy-wide rebound remains unknown and disputed, our understanding of the current state of knowledge is that we take the ability of energy efficiency to deliver substantial reductions in greenhouse gas emissions for granted. Even the possibility of 'backfire', i.e. that economy-wide rebound exceeds 100%, cannot be completely ruled out.

3.3 *Developing fossil energy with CCS and renewable energy in parallel may lower system-wide performance*

'Carbon lock-in' refers to a situation where, due to a variety of forces, a type of inertia is present whereby efforts to implement greenhouse gas-saving measures are hindered; and thus fossil-fuel dependencies are perpetuated. The forces adding to lock-in may be of technological, institutional or social nature (Unruh, 2000). Arguably, a condition of carbon lock-in may explain the seemingly paradoxical situation where, theoretically, technological fixes to the climate change problem appear to exist and be affordable, but in practice, the diffusion of the technologies is slow (Unruh, 2000; 2002). Similar arguments arise, independently, also in the political science literature on energy technology (Moe, 2010).

Indeed, some of the arguments presented in the current paper are related to, and may be seen as part of, the concept of carbon lock-in, but an elaboration is beyond the scope of this paper. In this particular section, we discuss carbon lock-in in the context of one specific characteristic of typical climate change mitigation scenarios; namely, the future co-evolution of fossil energy with CCS and renewable energy. We point out that while envisaged least-cost pathways to climate stabilization involve fossil energy with CCS and renewable energy developing in tandem, system-wide performance is not maximized in such conditions. In short, this is because many of the forces that have created the carbon lock-in of today will continue to be exerted by fossil energy systems also in the future, even if these systems are combined with CCS. We elaborate on this argument below, after first briefly introducing factors that may lead to carbon lock-in and that are relevant for the present discussion.

While recognizing that explanations for carbon lock-in may be sought at the micro or macro level, and that forces acting within individual firms can also contribute to lock-in (Unruh, 2000), we here focus on externalities in networks of inter-related technologies and institutions. In society, such network externalities give rise to groups of compatible components forming clusters, with positive externalities reinforcing compatible components' competitiveness and viability, while negative externalities raise barriers for incompatible elements. One example from the historical record is the co-evolution of roads, petrol-fueled automobiles and oil pipelines, and an array of related public and private institutions (Grübler et al., 1999; Unruh, 2000; Moe, 2010). Unruh (2000) recognizes three types of macro-level network effects. The first relates to connections and dependencies among industry actors, such as coordination to produce complimentary products and the introduction of standards and conventions. Such relationships create favorable conditions for complimentary industries, but create barriers for new solutions. The second type has to do with the way in which projects are financed: Profitable firms tend to direct financing back to their own core competencies, and risk-aversive lenders may have a similar preference towards existing solutions. Finally, externalities arise from private and public institutions with bonds to technological systems; some examples are user-created organizations, educational establishments and professionals representing certain disciplines, industry associations and regulatory frameworks (Unruh, 2000).

Returning to the case of CCS, our concerns stem from two observations. First, comparative climate change mitigation model runs tend to find that scenarios with co-evolutions of fossil energy with CCS and renewable energy show significantly lower mitigation costs than scenarios with only non-fossil energy (IEA, 2010a; Krey and Clarke, 2010). In one assessment (IEA, 2010a), excluding CCS from the set of available options raises overall costs to achieve stabilization by 70% (IEA, 2010a). The second observation is that implementing CCS on a large scale will prolong the life spans of systemic factors adding to carbon lock-in, compared with the case if only non-fossil solutions were implemented. For example, as investors into long-lived capital assets in connection with fossil fuels will expect returns on their investments, premature (in economic terms) efforts to phase out fossil fuels may be met with resistance. More broadly, policy-makers will have to withstand additional rounds of lobbyism and many other influences from groups disadvantaged by a phase-out of fossil energy (regardless of whether CCS is used), and, because industries facilitating the use of fossil energy resources are kept alive, the tendency for investments to be directed to fossil fuel-based technologies will to some degree persist.

Our intent here is not to argue against CCS as such. Indeed, developing CCS may be beneficial for other reasons. From another viewpoint, due to CCS being more compatible with current systems than competing renewable power generation technologies, developing large-scale CCS may be regarded as a means to overcome lock-in barriers to climate change mitigation in the short-term (Unruh and Carrillo-Hermosilla, 2006; Praetorius and Schumacher, 2009). Also, one could argue that a pragmatic approach to climate policy warrants that an opportunity is kept open for the fossil fuel industry to radically reduce its emissions. This does not, however, alter the fact that fossil energy with CCS will, in the overall picture, not exert synergistic effects on renewable energy deployment, but conversely, raise barriers. Similarly, renewable energy systems can raise barriers for CCS. Our main concern, and the key point of this discussion, is the imbalance between the envisaged least-cost pathways to climate stabilization (i.e., pathways in which fossil energy with CCS and renewable energy develop in parallel), and the pathways in which systemic forces (externalities) are aligned in such a way that system-performance is advanced (i.e., pathways in which fossil energy is phased out altogether).

3.4 The notion of absolute decoupling is not supported by historical records

The concept of decoupling lies at the heart of the technology optimism permeating current climate policies. Decoupling can refer either to a decline in environmental impact per unit of economic output (relative decoupling), or to an absolute decrease in environmental impact as income grows (absolute decoupling). If the latter measure is expressed in units of tonnes of CO_2 per year, the former would be in units of CO_2 per dollar or similar. It is important to distinguish between these two interpretations (Jackson, 2009). Evidence of relative decoupling has been put out to justify an optimistic view on technological fixes to environmental problems (Ausubel, 1996). However, as have been noted repeatedly (Arrow et al., 1995; Jackson, 2009; Speth, 2008), only limited conclusions can be drawn from relative measures; it is vital also to address absolutes. The historical records provide no evidence to suggest that sufficient absolute decoupling of climate change impact can take place in coming decades (Jackson, 2009). While this does not rule out the possibility that absolute decoupling can take place in the future, it does show that future developments in many aspects must be fundamentally different from historic developments.

Furthermore, when studying decoupling trends of post-industrialized countries, shifting trading patterns obscure the picture and lead to too optimistic conclusions. This is because of a shift of dirty manufacturing activities to less wealthy nations. For example, in recent decades, CO_2 emitted in China to produce products for export has increased rapidly (Weber et al., 2008). Correspondingly, significant increases with time are evident in estimates of CO_2 embodied in imports to wealthy nations from China (Reinvang and Peters, 2008; Weber and Matthews, 2007). From the results of Wiedmann and colleagues (2010), analyzing production and consumption based emissions for the UK in the period 1992-2004, one may observe that an apparent 5% decline in CO_2 (derived from domestic emissions inventories reported to UNFCCC), turns into a 8% increase, if changes in emissions embodied in international trade are taken into consideration. A recent study by Peters et al. (2011) confirms the general validity of these anecdotal reports, estimating that the net emission transfer to post-industrialized countries increased from 0.4 Gt CO_2 in 1990 to 1.6 Gt CO_2 in 2008 – a growth that more than outweighs the wealthy nations' emissions reductions commitments under the Kyoto Protocol.

A further element which may be noted is that rooted in climate change mitigation scenarios (IEA, 2010a, b) is an assumption that sufficient capital can be made accessible to finance the (capital-intensive) transition away from conventional and towards lower-carbon energy systems. However, investments in renewable energy assets – and sustainability-focused investments in general – tend to bring long-term payoffs, not short-term profits (Jackson, 2009). The ability of current financial systems to foster sufficient long-term investments in sustainability is yet to be demonstrated.

3.5 Linkages between environmental pressures are likely to complicate mitigation

Due to incomprehensible complexities in biophysical and social systems, impact and mitigation assessments must to a large extent take a reductionist approach to understanding and addressing environmental problems, largely neglecting linkages between individual pressures and systems. As is pointed out by van der Voet and Graedel (2010), not only do linkages connect systems with strong dynamic behavior, but the linkages are in themselves dynamic – this contributes to the complexity.

The notion that individual problems can be assessed and treated in isolation is problematic on at least two levels. First, there is a danger that interactions among different problems give rise to nonlinearities which go unaccounted for in impact assessments. For example, biodiversity loss may increase ecosystems vulnerability to climate change, and nitrogen-phosphorus pollution may weaken marine ecosystems so that less carbon is absorbed from the atmosphere (Rockström et al., 2009). Second, approaching many biophysical limits simultaneously implies a high risk of problem shifting, that is, solving one problem while generating another; and deployment of solutions to overcome one biophysical limit may be hindered by other physical constraints. In a simpler world where GHG emissions were the only environmental pressure, one would not need to consider effects of renewable energy systems on ecosystems, impediments to development of new technologies due to mineral resource scarcity, and water demand following employment of new energy solutions. In reality, achieving sustainable energy supply requires technologies that can deliver sufficient degrees of de-carbonization in spite of, and without adding unacceptable momentum to, ecosystem degradation and resource scarcities.

3.6 Future demands for energy services may be underestimated

We here call attention to two reasons why the potential for future demand for energy services may be underestimated. First, current engineering-economic models are based on satisfying existing categories of energy demand. Even if demand in these categories is assumed to grow, there is a natural limit: upscaling demand for already known consumption categories cannot account for all growth in energy use in the long term, because in reality, new categories of demand arise and grow – sometimes to become important in the aggregate. This is what happened with rail transport in the 19th century, what may be happening with air transport in the 20th and 21st centuries, and what may start to happen with space tourism in the 21st century. The issue of entirely new categories of demand emerging over time may be seen as special type of rebound effect (Sorrell 2009; Jenkins et al., 2011), and is thus related to the discussion in Section 3.2.2.

A second problem with contemporary energy scenarios is that linkages between energy requirements and other (non-energy) resource constraints (cf. Section 3.5) are not considered. It is conceivable that such linkages may give rise to unanticipated growth in already existing categories of energy demand. This is what may happen with energy use associated with pumping, treatment, and desalination of water as freshwater increasingly is becoming scarce in many places (UNEP, 2010a; UNESCO, 2009), and with energy requirements of primary metal extraction as the quality of available metallic ore resources deteriorate (Norgate, 2010; Norgate and Jahanshahi, 2010).

4 Final remarks

Technological solutions are vital in solving global environmental problems, including climate change. However, the conception of technology as a panacea for global environmental problems lacks solid justifications. In this article, we have challenged the notion that energy efficiency and 'clean' energy technologies can deliver amounts of climate change mitigation sufficient to deem fundamental changes in social and economic structures to be unnecessary. The famous wedge analogy introduced by Pacala and Socolow (2004), where, conceptually, different mitigation strategies add up to form a stabilization triangle, is, while intuitive, not accurate. In reality, often it is not reasonable to view climate change mitigation strategies in isolation from each other, as independent of the baseline trends below which the stabilization wedges are conceptualized, and without taking into consideration other environmental pressures not directly related to climate change.

A thorough understanding of how 'ripple' effects of mitigation measures play out on a macro scale lies in the future, but, as is to some extent reflected in this article's list of references, a fair amount of relevant research findings already exists for evaluating the system-wide effects of mitigation measures. The urgency of tackling climate change makes this a crucially important area of research. Equally important is research investigating how indirect, countervailing effects of mitigation measures may be addressed and how real mitigation at the system-wide level may be realized. If society becomes receptive to the idea that developed nations abandon growth-oriented economies, researchers will be asked to investigate ways in which a new macro-economy, which does not require growth to preserve economic stability, can be developed (Jackson, 2009; Victor 2010). Yet another salient issue is increasing the resiliency of financial institutions to reward sustainability-focused investments that bring long-term benefits.

More profound changes in social and economic structures may render possible degrees of climate change mitigation beyond what can be achieved by technology within current frameworks. The importance of preserving the climatic conditions to which the human civilization is adapted, and restoring the ecological basis on which all human activities rely, can hardly be overstated. If the optimism on behalf of technological solutions is misconceived, scholars and policy makers must start now to explore ways in which mitigation can be realized also through alternative avenues.

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