5. Be policy-relevant

Attaching the project to a politically salient issue has increased the influence of many ideas among policymakers; for example, 'ecosystem services' (which include climate-based services) in nature conservation can show that doing the right thing for nature doesn't necessarily mean doing the worst thing for the economy (perhaps a Faustian bargain, nevertheless). A useful example of astute framing of evidence can be viewed by analyzing the campaign of the Royal Society for the Protection of Birds (RSPB) against the trade in wild birds. The RSPB was able to 're-frame' their evidence against wild bird trading when they sensed an opportunity to package it in a politically salient way. They had campaigned for a long period of time to achieve a European Union ban, presenting clear evidence that the trade was ongoing. Initially, this evidence was framed on animal welfare grounds, but this line of argument failed to impact on policy. However, when the bird flu crisis struck, the RSPB were able to show that the trade in wild birds was a serious issue for human health, potentially providing an avenue for spreading the disease further. This salient framing of the same evidence had an immediate influence on policy[17].

Where possible, climate science should be communicated in a policy-relevant way (the IPCC is meant to be 'policy relevant' after all), showing that doing the right thing for climate is not always alien to other political priorities. Of course, this will not always be possible, but climate scientists can productively seek a better understanding of current political priorities, and consequently package their evidence in a more influential way.

Winning the battle

I have argued that when presenting climate science to policymakers, it is rarely adequate for evidence to be merely 'correct'; it must also be persuasive. Thus, climate scientists would do well to pay more attention to understanding how policy negotiations work, what could be done to ameliorate differences between decision-makers, and how science could be presented in persuasive form. Because, at times, researchers "are informing battles," but are often "not providing the knowledge needed to win the war," and thus they must start to work "outside [their] comfort zone"[18].

The battle to protect the world from climate change will not be won by firing a single canon repeatedly at decision-makers, loaded with a slightly larger cannonball each time, proving that humans are responsible for climate change or expecting extreme climate events to convince policymakers to take sudden action. Rather the battle may be won by firing a broadside shot at policymakers, loaded with targeted information about how policy systems work and which issues are particularly prominent in holding up meaningful action, as well as containing astutely framed practical solutions. In directing these efforts wisely, climate scientists can win battles. Otherwise, in several years' time, policymakers might again be vociferously blaming another extreme event on climate change and leave climate scientists wondering why little attention was paid to the accumulating evidence. ❐

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COMMENTARY:

A better currency for investing in a sustainable future

Michael Carbajales-Dale, Charles J. Barnhart, Adam R. Brandt and Sally M. Benson

Net energy analysis should be a critical energy policy tool. We identify five critical themes for realizing a low-carbon, sustainable energy future and highlight the key perspective that net energy analysis provides.

Most energy planning efforts consider primary energy production by countries, industries, companies or projects. This focus on gross production of primary energy does not reflect the reality that some fraction of this gross production must be invested in sustaining and growing the energy system itself, as well as in processing and transforming energy to provide the useful energy services we desire. Put simply, we need to 'spend' energy to 'make' energy. If the fraction of energy used by the energy system is constant, tracking and forecasting the evolution of the energy system without considering the energy reinvestment may be adequate. However, new energy resources, new energy conversion and storage devices, and new global supply chains will affect the fraction of energy reinvestment required to support societal energy demands. Given the large changes required in coming decades to supply larger amounts of energy in a more sustainable fashion, it is clear that metrics of energy system productivity will be an essential tool for guiding research, policy and investment.

Most economic activities 'consume' more energy (actually, free energy) than they 'produce'. Consider steel production: factories consume energy to turn iron ore into useful material products. In contrast, primary energy processes must supply much more energy than they consume. For example, the oil industry historically has output tens to hundreds of times more energy than it consumes in extracting and refining oil[1–3]. Or, over its lifetime, a modern wind turbine produces about 80 times more electrical energy than consumed in manufacture and installation, while solar photovoltaic systems produce about 10 times more[4]. Shifting the mix of energy supplies between traditional fossil fuels and renewables will affect the energy needed to transform and sustain our energy system.

Tracking these levels of productivity is the domain of net energy analysis (NEA), which combines analysis of primary energy resources with engineering analysis of device efficiencies, as well as efficiencies and transformations in the broader technological system. NEA supplements traditional economic analyses by systematically accounting for the energy consumed, directly and indirectly, by the energy sectors during the lifecycle of energy production (Fig. 1). NEA can complement traditional energy planning, which focuses primarily on minimizing the financial cost of energy production. For example, using NEA, the success of policies to promote photovoltaics can be judged on cost reductions and installed capacity, as well as on net energy provided to society and net emissions avoided. For photovoltaics, this perspective would prioritize photovoltaics with high efficiency and low energetic inputs for manufacturing. NEA would also favour manufacturing photovoltaic panels in locations with low emissions and high-efficiency energy production, and favour deployment in locations with higher solar irradiation and where the photovoltaic electricity produced can offset electricity with a high carbon footprint[5].

Here, we outline five themes that are important to low-carbon, sustainable energy policy and show that, in each case, there are clear benefits to explicitly incorporating these factors using NEA.

Valuing energy resources

NEA provides a way to value energy resources and their production technologies by comparing their ability to render primary energy resources useful for societal work. One could ask, for example, if I have a unit of energy to invest in building new energy capital, what is the most valuable energy investment? Today, every unit of electrical energy invested in wind power returns about 80 units of electricity. For that same unit of electrical energy, solar photovoltaics return about 10 units of electricity[4]. This is not only because wind turbines are more efficient and have higher capacity factors than solar photovoltaics, but also because wind turbines require much less energy to manufacture per unit of capacity[6]. If maximizing growth of renewable energy output is the goal, clearly wind power is a better energy investment today. Metrics measuring energy returns provide a complementary method by which to value primary energy resources, and can complement traditional economic measures (for example, levelized cost of electricity in dollars cost per kilowatt hour supplied).

Net energy fuels the economy

The availability of energy fuels economic processes[7,8] and economic growth[9]. If the energy sector provided only enough energy to fuel its own processes, thereby providing no net energy, it would be of little use to society. An analogy can be made with the steel industry. There would not be a steel industry if total steel production supplied only enough steel for the mining and processing equipment used by the steel industry itself. Consider the photovoltaic industry. Imagine building a photovoltaic manufacturing complex whose only source of electric power is on-site photovoltaic panels. All panels produced would be installed onto new plants that produce yet more panels. Theoretically (barring other resource constraints) the entire globe could be covered with photovoltaic panels. However, the rate at which this industry could grow is constrained by the amount of electricity produced by the panels themselves.

Clearly, the real photovoltaic industry is not so constrained. The industry can 'borrow' energy from the rest of the energy sector. But is the solar photovoltaic industry currently self-sustaining or parasitic on other energy resources? Until 2012, the industry was running an 'energy deficit',

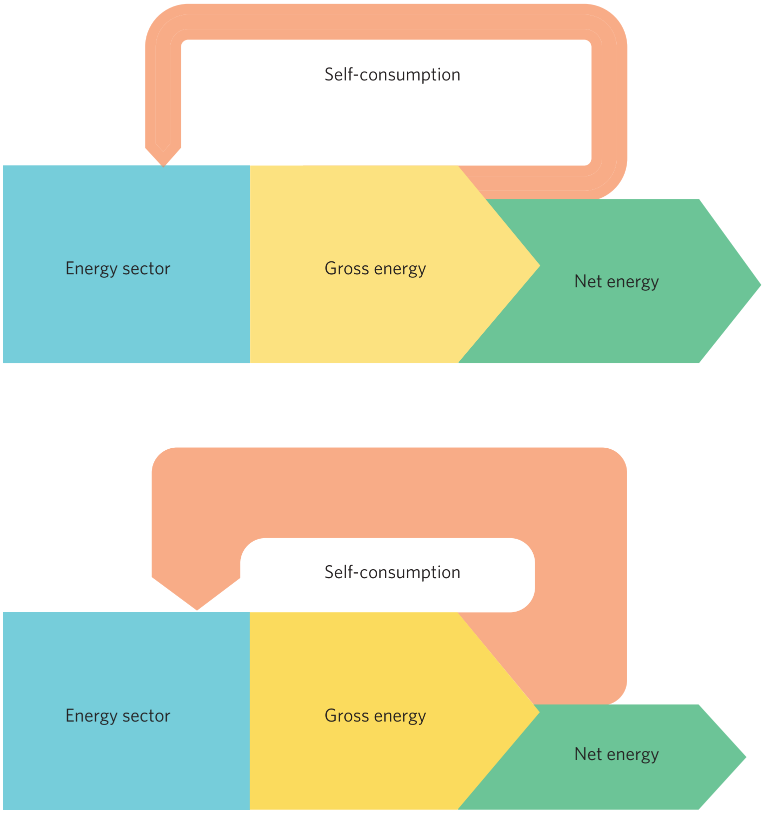

Figure 1 | Net energy analysis (NEA) studies the net output of energy-producing technologies, accounting for the energy consumed, directly and indirectly, by the energy sectors, in contrast to the gross energy production measured by the International Energy Agency and US Energy Information Administration in their analyses. Only net energy is available for end uses within society. As net energy output from a system declines (top to bottom), less energy is available to society per unit of total energy consumption, increasing investment requirements and environmental impacts of final energy use.

borrowing more energy than it produced, causing a net reduction in the amount of electricity available for other uses. Such an energy deficit can be supported as long as the photovoltaic industry remains a small portion of the overall energy sector; less than 1% in 2012[10]. However, as the industry grows, such a deficit would become a burden on global energy supply. Today in 2014, global photovoltaic installations have an average energy payback time of two years. This means that the industry is now self-sustaining on an electrical energy basis[5]. However, at the current growth rate of 40% per year, the photovoltaic industry consumes the equivalent of around 90% of its own electricity output. If these high growth rates are to be sustained, additional efforts will be needed to reduce the energetic inputs for photovoltaic systems.

Environmental impacts

Human energy consumption diverts energy stocks and flows from nature to society, and deposits waste products into the environment. Fossil fuels provide 85% of current primary energy supply and contribute some 60% of total greenhouse gas emissions[11]. Climate impacts of renewable resources are much smaller, but renewable energy production can have land and ecosystem impacts. Because impacts from primary energy extraction scale with total energy consumption, energy production pathways with high net energy returns help reduce environmental impacts. In essence, every unit of energy consumed within the energy sector to supply our needs acts as a multiplier that increases environmental impacts associated with our energy use.

The Canadian oil sands provide a pertinent example. These resources require more energy for their extraction and processing than conventional oil[3,12]. This is due fundamentally to the challenging physical properties of the resource: the bituminous oil sands are viscous and difficult to extract. In addition, the resulting product must be more intensively processed to produce useful fuels for consumers. The oil sands industry supplies about five times more energy to society than consumed from outside sources[12]. This can be compared with traditional oil resources, which supply ten to twenty times the energy consumed in the production process[13]. This increased energy intensity results in larger climate impacts per unit of energy supplied from the oil sands[14].

Early technology appraisal

NEA can identify potential costs and barriers to technology development that a traditional financial analysis might not. Nascent technologies, with low technology readiness levels, often have highly uncertain economics, particularly when considering development of new materials, new production processes or translating lab-scale prototyping to large-scale production. However, energetic and material requirements are subject to fundamental physical laws, which can provide bounds on technological development. For example, there is a minimum amount of energy required to purify silicon for production of photovoltaic cells, which is defined by the chemical exergy of pure silicon. This fundamental physical reality provides a benchmark by which to assess the performance of current production processes and what may be realistically achieved through further research and technology development. Performance targets for efficiency and durability can also be established by net energy analysis. For example, a recent study analysing the energy balance for large-scale hydrogen production showed that a solar photoelectrochemical cell with 5% conversion efficiency requires a lifetime of at least five years before net energy returns are positive[15]. Extending the lifetime up to 30 years can yield devices that deliver six times as much energy as was used in their manufacture. Similar work has shown that for grid-scale electricity storage, increasing the number of times that a battery can be charged and discharged is the single-most important improvement that can be made[16].

Managing the energy transition

NEA allows quantitative comparisons of the energetic performance of various transition pathways. We can also estimate what rate of growth an energy industry can support while still maintaining an energy profit[5,6]. In this way, NEA complements financial and environmental analyses in guiding sound policy decisions. For example, one pressing question is: 'What should be done with excess, renewably generated electricity?' Curtailing wind and solar electricity seems like a frustrating waste of energy. Recent policy actions in Germany and California mandate grid-scale energy storage as a method to reduce resource curtailment[17]. Due to the cost of building storage, it is often favourable from an energetic perspective to simply curtail the wind resource rather than store it in batteries[4]. Whereas market forces favour storage options with low financial costs, such as traditional lead-acid batteries, NEA shows that storing electricity with lead-acid batteries cuts energy returns by more than a factor of two and increases carbon intensity by more than 50% (ref. 16). NEA also tells us that there is a great benefit to combining low energetic cost renewables and storage technologies. The wind industry can 'afford' over 72 hours of geologic storage (pumped hydro and compressed air energy storage) per unit of capacity installed while growing at 200% per year and still provide a surplus of electricity to society. Deploying 24 hours of battery storage per unit of installed capacity while trying to grow at only 50% per year pushes the photovoltaic industry into an energy deficit[6]. Faster growth rates of these industries means a faster transition to a more sustainable energy future. As such, NEA can beneficially inform policy decisions and guide investments away from promoting financially sound but environmentally imprudent technology choices.

Challenges

A number of challenges exist. One critique of NEA suggests that it provides the same information already contained in energy prices[18]. However, because of subsidies or other policy incentives, price can sometimes be a poor indicator of underlying value (or costs) of a resource. Another challenge is that NEA is hindered by a shortage of rigorous data. Indeed, we argue that more effort is needed to acquire high-quality data on the energetic inputs to all forms of energy used today and being considered for use in the future. The lifecycle assessment community is making progress in this regard, but more support and access to data is needed. A number of methodological issues within NEA are also being addressed by lifecycle assessment researchers due to the large overlap in the two techniques. There is a strong need to bridge the two disciplines.

Looking forward

The clearest answer to 'why is net energy important?' is that net energy, not money, fuels society. Energy expended in the extraction of energy is not available to provide the energy services that undergird our economies. Ultimately, the transition to a more sustainable energy system will require changing behaviour around societal use of energy. NEA can guide decision-makers at all levels, from households to governments. When managing complex systems, it is vitally important to have the right set of indicators to guide our decisions[19]. We would not drive a car without a speedometer, nor fly a plane without an altimeter. Our economies are incredibly complex systems that require multiple, complementary indicators to guide decision-making. We have shown how NEA adds a beneficial, physical perspective to traditional economic analysis along a number of different dimensions. We believe it is time for policymakers to make greater use of this critical tool. We hope that this Commentary will encourage future NEA studies and their use as a vital part of building a sustainable future. ❐

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COMMENTARY:

Climate engineering reconsidered

Scott Barrett, Timothy M. Lenton, Antony Millner, Alessandro Tavoni, Stephen Carpenter, John M. Anderies, F. Stuart Chapin III, Anne-Sophie Crépin, Gretchen Daily, Paul Ehrlich, Carl Folke, Victor Galaz, Terry Hughes, Nils Kautsky, Eric F. Lambin, Rosamond Naylor, Karine Nyborg, Stephen Polasky, Marten Scheffer, James Wilen, Anastasios Xepapadeas and Aart de Zeeuw

Stratospheric injection of sulphate aerosols has been advocated as an emergency geoengineering measure to tackle dangerous climate change, or as a stop-gap until atmospheric carbon dioxide levels are reduced. But it may not prove to be the game-changer that some imagine.

In the 1992 Framework Convention on Climate Change, virtually every country agreed to stabilize concentrations of greenhouse gases (GHGs) in the atmosphere at a level that would avoid dangerous climate change. Since then, however, international cooperation in limiting emissions has been ineffectual and concentrations have continued to rise. Recently, there has been more discussion of limiting climate change by geoengineering, a term taken here to be synonymous with solar radiation management, through the injection of sulphate aerosols in the stratosphere. The technique is even mentioned in the Intergovernmental Panel on Climate Change's 2013 Summary for Policymakers[1].

Two powerful arguments have been made for using geoengineering: as an emergency measure[2] and as a stop-gap[3]. We analyse both proposals from two perspectives: (1) effectiveness — would the use of geoengineering achieve the stated goal? (2) political feasibility — is there a reasonable prospect that the international political system would allow geoengineering to be used to achieve the stated goal? Our main conclusion is that, when the use of geoengineering is politically feasible, the intervention may not be effective; and that, when the use of geoengineering might be effective, its deployment may not be politically feasible. On careful reflection, geoengineering may not prove to be the game-changer some people expect it to be.

The effects of geoengineering

Among the many options for 'global dimming' aimed at limiting global warming, the simplest involves putting sulphate aerosols in the stratosphere to scatter sunlight[4]. This form of geoengineering could reduce temperature in the lower atmosphere quickly. It would also be relatively inexpensive to deploy and could be done unilaterally, without the need for international cooperation. Ironically, however, this is one of geoengineering's problems: its use might harm some countries (for example, by altering the monsoons) even if it were expected to help others. Geoengineering, particularly the use of stratospheric aerosols, poses a challenge for governance.

Of all the arguments against geoengineering, perhaps the one most frequently advanced is that knowledge of geoengineering's ability to cool the climate will reduce the incentive to cut emissions[5]. However, theory and laboratory experiments suggest that the failure to cut emissions can be explained by free-rider problems, including those associated with uncertainty about the true threshold for dangerous climate change[6]. Belief that geoengineering could serve as a cheap and quick fix might further dampen the incentive to cut emissions, but it doesn't seem probable that this belief will, by itself, cause concentrations to exceed dangerous levels. In any event, knowledge of geoengineering cannot be erased.

It is important to understand that geoengineering cannot be used to preserve today's climate. Sunlight scattering would act on shortwave radiation, and GHGs affect long-wave radiation. In theory, atmospheric