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Publication Date

2018-03-01

DEEP GREEN: Detailed Environmental and Economic Projections for Global Renewable Energy and Emissions scenarios

DEEP GREEN Documentation: Overview of DEEP GREEN

Version 1.0

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March 2018

DEEP GREEN DOCUMENTATION REPORTS

Published

Overview of DEEP GREEN

Planned

Review of Literature
Objectives and Methods
Lifecycle Energy Use
Lifecycle Materials Use and Water Use
Land Use
Economic Relationships
Air and Water Emissions
Albedo
The Nitrogen Cycle
The Carbon Cycle and Climate
Air Quality
Impacts of Air Pollution
Impacts of Climate Change
Water Quality and Impacts of Water Pollution
Jobs
Noise and Impacts on Aesthetics and Biodiversity
Energy Security
Valuation of Impacts
The Social Discount Rate
Energy-System Capital and Operating costs, System Aging functions, and Total
Lifetime costs
Government Program Subsidies and Non-Cost Transfers
Results from DEEP GREEN

We revise the documentation reports periodically. The current versions of the documentation reports are available from Delucchi's faculty web page, <https://madelucchi.berkeley.edu>. Archived versions are at <http://escholarship.org>.

ACKNOWLEDGMENTS

I am responsible for this work. This is not a publication of Lawrence Berkeley National Laboratory or the Institute of Transportation Studies at UC Berkeley.

Early versions of some parts of this documentation appeared as supplemental material in:

M. Z. Jacobson, M. A. Delucchi, et al., "100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World," *Joule* **1**: 1-10 (2017). <http://dx.doi.org/10.1016/j.joule.2017.07.005>.

M. Z. Jacobson, M. A. Delucchi, G. Bazouin, Z. A. F. Bauer, C. C. Heavy, E. Fisher, S. B. Morris, D. J. Y. Piekutowski, T. A. Vencill, and T. W. Yeskoo, "100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for the 50 United States," *Energy & Environmental Science* **8**: 2093-2117 (2015). <http://dx.doi.org/10.1039/c5ee01283j>.

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OVERVIEW OF DEEP GREEN

INTRODUCTION

Objective

The world is at a crossroads. Recent analyses show that it still is possible to limit global temperature increase to no more than 1.5 degrees C above pre-industrial levels, but that to achieve this the world must transition rapidly towards sustainable, low-carbon energy systems (Millar et al., 2017). However, there are many potential energy-system transition pathways, and they should be evaluated not only by their impacts on climate, but also by their impacts on air quality, water use, energy security, land use, biodiversity, human health, alleviation of poverty, job creation, economics, and more. At present, no tool or modeling system provides such a comprehensive, multi-impact, policy-relevant social-cost-benefit evaluation of energy-system transitions. To meet this need, we propose to develop, document, and run a new modeling system, Detailed Environmental and Economic Projections for Global Renewable Energy and Emissions sceNarios (DEEP GREEN), to estimate the lifecycle environmental, economic, and energy-security impacts and full social costs and benefits of a wide range of transition scenarios for sustainable energy systems, including 100% zero-emission systems, for the US, China, India, Russia, and most other countries of the world.

Background

Although there are many studies of deep decarbonization¹ of energy systems (e.g., Parsons-Brinckerhoff, 2009; Price-Waterhouse-Coopers, 2010; ECF, 2010; EREC, 2010; NRC, 2010; NRC/NAE, 2010; NREL, 2012; Williams et al., 2012; Mai et al., 2014; Williams et al., 2014; Cochran et al., 2014; Connolly and Mathiesen, 2014; Hohmeyer and Bohm, 2014; Mathiesen et al., 2015; Teske et al. 2015; Morrison et al., 2015; DDPP, 2015; Jacobson et al., 2015a, 2015b; Frew et al., 2016; Breyer et al., 2017; Heard et al., 2017; Plessmann and Blechinger, 2017; Jacobson et al., 2017; Ram et al., 2017; see Cochran et al., Heard et al. and Jacobson et al. for additional literature reviews), and many studies of the environmental impacts of deep decarbonization (e.g., USEPA, 2011; Shindell et al., 2012; Siler-Evans et al., 2013; Masanet et al., 2013; West et al., 2013; Arent et al., 2014; Thompson et al., 2014; Menendez et al., 2015; Aman et al., 2015; Driscoll et al., 2015; Klein and Whalley, 2015; Kouloumpis et al., 2015; Hertwich et al., 2015; Buonocore et al., 2016; Wiser et al., 2016a, 2016b; Berrill et al., 2016; Zhang et al., 2016, 2017; Gibon et al., 2017; Rauner and Budzinski, 2017; Vaishnav et al., 2017; see Deng et al., 2017, and Chang et al., 2017, for reviews), there is no existing research or modeling system that accounts for all – or even most – of the elements needed for a complete,

¹Throughout we use the term “decarbonization” broadly, to cover everything from simply reducing (but not eliminating) carbon dioxide (CO₂) emissions *per se* (as might be the case with some bioenergy strategies) to essentially eliminating emissions of all air pollutants and GHGs and greatly reducing other impacts (e.g., on water quality) as well (as can be the case with electrification strategies using wind, water, and solar power).

detailed, internally consistent analysis of the full social costs and benefits of deep-decarbonization scenarios for all energy-use sectors in the world.

DEEP GREEN will fill these gaps by creating a novel, comprehensive, integrated framework with the components and linkages shown in Figure 1: lifecycle use of energy, materials, and water; detailed treatment of transportation electrification; a model of the electricity transmission and distribution system; land use; economy-wide price effects, with feedbacks between prices, energy use, and materials use; emissions, including anthropogenic air pollutants and greenhouse gases, natural emissions, and water pollutants; surface albedo; the nitrogen (N) cycle; the carbon (C) cycle; air quality; climate change, with feedbacks to air quality and emissions; water quality; health, environmental, and economic impacts; noise and impacts on aesthetics and biodiversity; impact valuation; energy security; jobs; energy-system costs, incorporating explicit system aging functions; government program subsidies; non-cost transfers; and total social lifetime costs and benefits. DEEP GREEN will include all energy-use sectors (residential, commercial, industrial, transportation, agriculture/forestry/fishing, other) and a diverse portfolio of energy technologies (solar, wind, hydro, geothermal, nuclear, bioenergy, fossil fuels, carbon capture and sequestration, and more). It will use a unified, detailed set of primary parameter values and functions, including GDP (Gross Domestic Product) per capita, valuation functions, the discount rate, and technology characteristics, across all relevant modeling domains including energy use, emissions, air quality, climate change, impacts, and valuation. It will properly account for the disproportionate impacts of climate change, air pollution, and other environmental problems on the world's poorest and most vulnerable populations.

By identifying low-cost, environmentally and economically sustainable pathways for all energy-use sectors, and by elucidating the important drivers, characteristics, risks, and benefits of sustainable solutions, results from DEEP GREEN can help policy makers, researchers, and public-interest groups design and implement robust, socially beneficial policies for climate-change mitigation, energy and economic development, and environmental protection. DEEP GREEN will address underexplored technical and economic research questions regarding energy resources, new energy technologies, energy transmission and distribution, land use, energy/economic-system interactions, C-cycle/N-cycle/air-quality interactions, the electrification of the transportation sector, and more. Because DEEP GREEN will be the most comprehensive tool of its kind, it will provide the most scientifically sound basis for measurably improving economic, social, and environmental well-being related to the production and use of energy.

RESEARCH PLAN AND METHODS

Overview

Our overall research plan is to develop the DEEP GREEN system delineated in Figure 1, create a wide range of transition and end-state scenarios, and run DEEP GREEN solving algorithms to find scenarios with low global social costs.

DEEP GREEN will represent year-by-year transition paths to long-run low- to zero-carbon energy systems, along with a “business as usual” (BAU) scenario, and will

estimate physical impacts and final social cost-benefit results for the US, China, India, Russia, Indonesia, Brazil, Nigeria, Japan, Mexico and most other countries of the world – a total of 139 countries with about 95% of the world population (see Jacobson et al, 2017). For the transition pathway and end-state scenarios, some variables will be specified for each country, and some will be specified for various groupings of countries into “scenario regions” based on geopolitical, economic, and technical considerations. An example of one possible grouping is the 16 regions used in the USEIA (2017) *International Energy Outlook*: the US, Canada, Mexico/Chile, OECD (Organization for Economic Cooperation and Development) Europe (generally Western Europe), Japan, South Korea, Australia/New Zealand, Russia, Eurasia and other non-OECD Europe (Eastern Europe and Central Asia), China, India, other non-OECD Asia, the Middle East, Africa, Brazil, and other non-OECD Americas (South and Central America and Greenland).

DEEP GREEN will estimate differences between the decarbonization scenarios and the BAU in terms of physical impacts (e.g., changes in water quality and in mortality related to air pollution), energy-system costs (capital costs, total lifetime costs, costs by end-use sector and technology, etc.), and the present value of total social lifetime costs.² The ultimate metric for each country, the total social lifetime cost of the energy-system pathway, is equal to energy-system lifetime costs (capital and operating costs discounted over the lifetime of the system), plus “external” costs, government program subsidies, and adjustments for non-cost transfers. External costs are costs to society that are not reflected in energy-system lifetime costs. DEEP GREEN will include the external costs of air pollution, climate change, water pollution, noise, impacts on aesthetics and biodiversity, and energy security, for all energy lifecycles including wind, water, and solar power (which in some analyses are incorrectly assumed to have zero external costs).³ Government program subsidies are direct public-sector expenditures in support of specific energy production and use activities, and DEEP GREEN will have a comprehensive accounting of any such subsidies that are real resource costs of energy use. Non-cost transfer payments are payments from consumers to producers or the government (or vice versa), and hence are not, on balance, real resource costs to society as a whole. As discussed below, DEEP GREEN will include appropriate adjustments for producer-surplus transfer payments from consumers to major energy producers, such oil producers, who garner large amounts of revenues in excess of economic cost.

In the estimation of the external cost of climate change and in the classification of oil-industry producer surplus, it matters whether one takes a country-specific (e.g., US) perspective or a global perspective. If for example one takes a US national perspective, then one ignores social costs to non-US entities. This means that one counts climate

² Note that while DEEP GREEN will estimate full social costs and benefits for a range of long-term energy transition scenarios, it will not analyze specific policies that might drive energy scenarios, such as carbon taxes, emission standards, or renewable-energy-production requirements. Scenarios in DEEP GREEN can be viewed as the results of unspecified policies.

³ In the future we may consider radiation risks associated with nuclear power, and accident and congestion impacts of transportation scenarios involving vehicle automation and expanded public transit. See the dashed boxes and lines in Figure 1.

change damages in the US *only*, but then also counts as a real cost to US consumers any producer-surplus payments to non-US producers (e.g., oil rents to foreign producers), because these payments constitute a real net welfare loss within the US. On the other hand, if one takes a global perspective, then one counts *global* climate-change damages from US greenhouse-gas emissions but does *not* count as a real cost producer surplus payments to non-US producers, because in a global accounting producer surplus is just a transfer from (US) consumers to (non-US) producers. (For oil-exporting countries, producer-surplus from oil exports counts as a benefit, or negative cost, from a national perspective.)

For every country, DEEP GREEN will estimate the global costs of total end-use energy *consumption*, without regard to transfer payments between countries or whether impacts occur inside or outside of national borders. For countries that import or export large amounts of oil (e.g., the China, the US, India, Japan, several European nations, the Organization of Petroleum Exporting Countries, Canada, Russia, Nigeria, and Venezuela), DEEP GREEN also will estimate costs from a country-specific perspective as well as a global perspective.

Figure 1 is a conceptual representation of the main components of DEEP GREEN. The model will be driven by exogenously specified decarbonization scenarios that initially affect energy use, materials use, and land use, which in turn affect and are affected by the economic system via price-change feedbacks. Final changes in energy use, materials use, and land use result in air and water emissions and also affect the nitrogen cycle, the carbon cycle, and surface albedo. These environmental perturbations then affect air quality, climate, and water quality, which in turn result in a range of health, environmental, and other impacts. These changes will be valued in utility-based monetary terms and combined with estimates of energy-system costs, energy-security costs, and other costs to produce an estimate of total social costs and benefits. Finally, we will use the social cost results from DEEP GREEN to perform structured scenario and sensitivity analyses (also known as “robust decision-making” analyses) to understand the key drivers of low-cost scenarios and identify pathways and scenarios that most consistently result in low global social costs for a given level of social benefit.

Because we already have done extensive work on many of the major elements of DEEP GREEN, our basic approach will be to build and expand on our previous work, and the work of others, to develop and integrate all of the components. The initial version of DEEP GREEN will prioritize completeness with workable simplifications (subject to empirically and theoretically determined constraints) over detailed representations, but because the modeling system will be modular, components can be made more detailed as more data, scientific understanding, and modeling resources become available. As discussed in more detail in the section “Data management plan,” we will build the model system on an open-source platform.

In the following sections we explain our approach to developing the components and linkages in the DEEP GREEN modeling system. We identify the existing work we will build upon, and then discuss any modifications and extensions to that work.

Decarbonization scenarios

DEEP GREEN will be driven by exogenous decarbonization scenarios that specify *the rate of adoption* of different energy-supply and end-use technologies, including efficiency measures (see the discussion of the energy system, next) towards different *final end states* of the energy system in the year 2100. We will consider, *inter alia*, the range of scenarios in the *Deep Decarbonization Pathways Project* (DDPP, 2015; Williams et al. 2014), and the 100% wind, water, and solar (WWS) power scenarios of Jacobson et al. (2015a, 2015b, 2017). Decarbonization scenarios also will specify other aspects of buildings and capital equipment that affect energy use, such as rooftop characteristics pertinent to energy production from photovoltaics.

As shown in Figure 1, the decarbonization scenarios also will affect certain aspects of land-use; specifically, they will affect how land would be used were it not used for energy production. This linkage from decarbonization scenarios to land use is necessary because the location and the technological and operational characteristics of energy production are partly determined by implicit or explicit assumptions about land-use policy, assumptions which are part of the *exogenous* scenario context and as such also govern what happens on land in the counterfactual of no energy production. For example, most bioenergy production scenarios implicitly recognize exogenous concerns regarding habitat protection, biodiversity, enhancement of ecosystem services, and so on, and accordingly construct bio-energy production strategies, such as planting grasses on so-called “degraded” or “surplus” land, to minimize the negative impacts (e.g., Dauber et al., 2012; Schueler et al., 2016; Zhuang et al., 2011; Shortall, 2013; Gelfand et al., 2013; Evans et al., 2015). However, because such concerns about the impacts of land use are part of the exogenously assumed scenario, they necessarily affect what happens on and to the land *regardless* of whether the land is used for energy development. This means, for example, that given an assumed context of significant concern for habitat protection, land restoration, etc., the logical no-energy-production counterfactual to a scenario in which biofuels are developed on “degraded” land can *not* be that the land otherwise would have been left degraded, but rather *must* be that some other environmentally beneficial action, such as restoration, would have been taken. And it is important to ensure that the counterfactual non-energy use of land as well as the energy-use of land are consistent with exogenous scenario characteristics because there is a great deal of difference, in terms of *any* environmental or climate-impact metric, between assuming (for example) that land remains degraded (which in this example is inconsistent with the exogenous scenario context of concern for ecosystem preservation, land restoration, etc.) and assuming (consistent with the exogenous scenario context) that the land, say, is restored to its original, non-degraded functioning.

Lifecycle energy use

To model lifecycle energy use, we will expand on our prior work simulating the conversion of all energy sectors to 100% wind, water, and solar (WWS) power, for 50 US states (Jacobson et al., 2015a, 2015b) and 139 countries of the world (Jacobson et al., 2017). These models estimate energy demand, system costs, and environmental impacts for business-as-usual (BAU) scenarios, which are based on detailed modeling by the US Energy Information Administration, and for the 100% WWS scenarios. Because DEEP GREEN will analyze a much wider range of transition scenarios and end states and will

have more detailed end-use sectors, we will extend the 100% WWS models (both the 50-state and the 139-country versions) as follows:

- i) Add stock turn-over models for all major energy-supply and energy-use technologies, to be able to simulate different rates of transition to different energy end-states.
- ii) Disaggregate the transportation sector to have more technologies and fuels/energy sources, with a more detailed treatment of electrification and hydrogen for road freight, shipping, rail, and air transport.
- iii) Extend the models to the year 2100 (currently the 100% WWS models can simulate transitions through the year 2075), although in some cases the extensions will assume constant values after 2075.
- iv) Develop reduced-form representation of power-system planning models, drawing on the LOADMATCH model (Jacobson et al., 2015a, 2018), the POWER model (Frew and Jacobson, 2016; Frew et al., 2016), and other sources (e.g., Blistine, 2017) in order to have more realistic estimates of the full cost of the electricity generation, delivery, and storage system within DEEP GREEN. This representation will account for uncertainty in demand and resource availability in the future. It will include a wide range of technologies and operational strategies for balancing supply and demand, including but not limited to centralized storage, decentralized storage, demand management, vehicle-to-grid systems, and re-use of automotive batteries (e.g., Gur et al., 2018).
- v) Include detailed estimates of the cost of providing ancillary services (e.g., frequency regulation, voltage control) for the power grid, both in the BAU and in cases with very high levels of variable generation (see McDonald et al., 2013; Ela et al., 2011; Willis, 2004; and Kirby, 2004; for overviews of and cost estimates for power systems and ancillary services).
- vi) Expand on the simplified representation of energy-use life cycles in Jacobson et al (2015a, 2015b, 2017), by developing detailed lifecycle energy input-output relationships from the Lifecycle Emissions Model (LEM), which was developed by the Principal Investigator (Delucchi et al., 2003). The expanded energy-lifecycle analysis will include energy end-use, fuel dispensing (where applicable), fuel distribution and storage, fuel production (e.g., petroleum refining), feedstock transport (e.g., shipping crude oil), and feedstock production.
- vii) Update technical and cost details for nuclear power, bio-energy, coal with CCS, and other technologies typically included in deep-decarbonization scenarios.

Lifecycle materials use and water use

In DEEP GREEN the use of energy affects the use of materials, and the use of materials affects the use of energy (Figure 1). A complete understanding of the energy and emissions impacts of deep-decarbonization strategies therefore requires a characterization of the impacts of new technologies on the lifecycle of materials. DEEP GREEN will incorporate updated and expanded materials and water-use lifecycles from the LEM (Delucchi et al., 2003), the Greenhouse gases, Regulated Emissions and Energy use in Transportation model (GREET; ANL, 2007), and other sources in the literature (e.g., Pehlken et al., 2017; Arent et al., 2014; Graedel et al., 2015; Hertwich et al., 2015; Helmers et al., 2017; Wiedmann et al., 2015). In DEEP GREEN the materials lifecycle will include the recovery and transport of raw materials (e.g., crude ore), manufacture and transport of finished materials (e.g., steel products, concrete), construction and assembly of energy-using equipment (e.g., vehicles, ships, power stations), maintenance and repair activities for energy-using equipment, and disposal of materials and equipment at end of life.

DEEP GREEN lifecycles also will include building, servicing, and providing administrative support for transportation infrastructure.

Land use

As shown in Figure 1, changes in land use affect the economic system, the C cycle, the N cycle, surface albedo, aesthetics and biodiversity, and emissions of GHGs and air pollutants. The land-use module of DEEP GREEN will estimate changes in land-use due to changes in energy use, and will contain land-use characteristic data needed for the other modules. Land-use change will be estimated on the basis of land-use footprint data from the LEM, GREET, and other sources (e.g., Geyer et al., 2013; Arent et al., 2014), adjusted to account for the effects of price changes on land use (see the “Economic system” section).

The data on land-use characteristics needed for a comprehensive model of the land-use-related effects of energy systems on climate and air pollution include the carbon content and carbon lifetime for different soils and plants, physical properties such as albedo, characteristics pertinent to the N cycle, such as C:N ratios, and emission fluxes of GHGs other than CO₂ (Delucchi, 2011). We will obtain these data from a variety of sources, including the Global Change Assessment Model (GCAM; Kim et al., 2006; JGCRI, 2016), the LEM, GREET, and reviews of the pertinent scientific literature.

Economic system (price effects)

Changes in the use of energy, materials, and land affect the prices of energy, materials, land, and related commodities, and these changes in price in turn feed back to affect demand for energy, materials, and land (Figure 1). To represent these market effects in Deep GREEN, we will start with GCAM to derive simple relationships between initial changes and price-mediated final “equilibrium” levels for energy use, land use, and materials use. We emphasize that the purpose of this module is not to finely simulate the performance of complex partial- or general-equilibrium economic models, but

rather to distill simple but still useful relationships that are more realistic than ignoring price effects altogether. (See Delucchi [2005c] for an example of a simplified method for incorporating price mechanisms into lifecycle energy models.) Note too that we assume that demand-side benefits – the services provided by the energy system – are the same in all scenarios.

We will revise and update GCAM functions as appropriate. In the case of land-use change (LUC) related to the development of bioenergy, we will refer to relationships and parameter values from the extensive recent literature on direct and indirect LUC from biofuels (see Qin et al., 2018, for a recent compilation of papers).

For DEEP GREEN we will develop our own oil-supply curves (or supply-response strategies) for the US, the Organization of Petroleum Exporting Countries (OPEC), Canada, Russia, China, Brazil, Mexico, and the rest of the world (ROW). Supply curves for the US and the ROW will be constructed based on detailed global data on oil recovery costs (this work already is partially completed). For OPEC we will construct a dynamic model of OPEC's production strategy that finds the oil supply path over time that maximizes the present value of OPEC's net revenue stream. A key feature of this model is that OPEC makes its optimal production decisions with the understanding that its choice of quantity to supply in a given period affects the world price of oil in subsequent periods. The result is a dynamic-feedback model that incorporates oil-market demand shifts that are endogenous with respect to OPEC's influence on the market price of oil. (Note that with other funding we already have begun work on this component.)

Air and water emissions

Emissions are a central component of DEEP GREEN, because they are affected by lifecycle energy use, lifecycle materials use, land use, and climate, and affect the C cycle, the N cycle, air quality, climate, and water quality (Figure 1). DEEP GREEN will generate detailed emissions of all species relevant to climate, air quality, and water quality, by technology, industry and sector, vintage (because emission factors change over time), and region. We will include non-combustion emissions (e.g., dust, evaporative emissions, process-related emissions such as from cement production, and so on) as well as combustion emissions, "natural" emissions (e.g., dust, volatile organic compounds from trees, and particulates from wildfires), and dispersed "area"-source water pollution (e.g., run-off from agriculture or mining) as well as point-source pollution. We will start with the comprehensive sets of US and global emission factors from the LEM (Delucchi et al., 2003),⁴ and update them with information from GREET, The Intergovernmental Panel on Climate Change (IPCC) emission-factor database (EFDB) for GHG emissions (IPCC, 2007a, 2007b), EDGAR 4.3.1 (Emissions Database for Global Atmospheric Research) (JRC, 2017), and other sources in the literature. We will ensure that our technology / sector / industry air-emission factors scale to be consistent with standard global inventories and projections from the IMAGE model (version 3.0)

⁴ Examples of results from the LEM are in Delucchi (1999, 2001), Lipman and Delucchi (2010), and Delucchi (2005b).

(Stehfest et al., 2014; PBL Netherlands Environment Agency, 2014) and the IPCC AR5 “Representative Concentration Pathways” (RCPs) (Moss et al., 2010; van Vuuren et al., 2011; RCP database, 2017). (Note that with other funding we already have begun work on this component.)

As shown in Figure 1, we will include appropriate feedbacks from changes in climate to changes in natural emissions.

Albedo

Changes in land use and vegetation can change physical parameters, such as albedo (reflectivity) and evapotranspiration rates, that directly affect the absorption and disposition of energy at the surface of the earth and thereby affect local and regional temperatures (Feddema et al., 2005; Lamptey et al., 2005; Lobell et al., 2006). DEEP GREEN will account for changes to surface albedo due to changes in land use driven by changes in energy use, such as land converted to the production of bioenergy crops or the installation of solar photovoltaic panels. (The effects of albedo change are discussed briefly in the section on the DEEP GREEN climate module.)

The nitrogen cycle

Anthropogenic inputs of nitrogen to the environment, such as from the use of fertilizer or the combustion of fuels, can disturb aspects of the global nitrogen cycle and have a wide range of environmental and health impacts (Vitousek et al., 1997; Galloway et al., 2003; Mosier et al., 2002). Nitrogen emissions to the atmosphere, as nitrogen oxides (NO_x), ammonia or ammonium (NH_y), or nitrous oxide (N_2O), can contribute to climate change through complex physical and chemical pathways that affect the concentration of ozone (O_3), methane (CH_4), nitrous oxide, CO_2 , and aerosols:

- i) NO_x participates in a series of atmospheric chemical reactions involving carbon monoxide (CO), non-methane hydrocarbons (NMHCs), H_2O , the hydroxyl radical (OH), O_2 , and other species that affect the production of tropospheric ozone.
- ii) In the atmospheric chemistry mentioned in *i*), NO_x affects the production of OH , which oxidizes CH_4 and thereby affects the lifetime of CH_4 .
- iii) In the atmospheric chemistry mentioned in *i*), NO_x affects the production of sulfate aerosol, which affects both climate and air quality.
- iv) NH_y and nitrate from NO_x deposit onto soils and oceans and then eventually re-emit N as N_2O , NO_x , or NH_y . Nitrate deposition also affects soil emissions of CH_4 .
- v) NH_y and nitrate from NO_x fertilize terrestrial and marine ecosystems and thereby stimulate plant growth and sequester carbon in nitrogen-limited ecosystems.

- vi) NH_3 and nitrate from NO_x form ammonium nitrate, which as an aerosol affects both climate and air quality.
- vii) As deposited nitrate, N from NO_x can increase acidity and harm plants and thereby reduce C- CO_2 sequestration.

DEEP GREEN will use a state-and-transition approach to account for all of these effects and predict the form and distribution of nitrogen compounds over time. The N-cycle model will comprise: *i*) a global set of ecosystem types, based on nitrogen-cycle-relevant characteristics of soil and biomass, such as C:N ratios; *ii*) a set of biogeochemical states, which represent a chemical form and a physical location for nitrogen; and *iii*) a set of transition pathways, which represent the chemical transformation and geographic movement of nitrogen compounds. Taken together the states and transitions will enable DEEP GREEN to map the time-path for nitrogen compounds in the environment. The N-cycle model structure and parameter values will be based on the relevant scientific and empirical literature (e.g., Xie and Ringler, 2017). (Note that with other funding we already have begun work on this component.)

Carbon-cycle and climate

DEEP GREEN will implement simplified global C-cycle and climate models, drawing on the science documented in the FUND model (Climate Framework for Uncertainty, Negotiation; Waldhoff et al., 2014), the open-source climate-system model Hector (Hartin et al., 2015, 2016), the LEM (Delucchi et al., 2003), the most recent state-of-the-science assessment by the IPCC (2013), and other sources (e.g., Arneth et al., 2017). The C-cycle model will represent C exchanges between atmosphere, ocean, and terrestrial biosphere reservoirs and the effect of anthropogenic emissions on these reservoirs. The uptake of CO_2 by oceans and the biosphere will be represented as a function of the atmospheric concentration of CO_2 . The C-cycle model will start with the amount of carbon in the three global reservoirs at the beginning of the year 1850, and then estimate, annually, fossil-fuel emissions to the atmosphere, anthropogenic land-use change (mainly deforestation) CO_2 emissions to the atmosphere, emissions of CO_2 from the oceans to the atmosphere, emissions of CO_2 to the atmosphere from decomposition of organic matter in the terrestrial biosphere (apart from that associated with anthropogenic land-use changes), uptake of atmospheric CO_2 by the oceans, and uptake of atmospheric CO_2 by the terrestrial biosphere via photosynthesis (also referred to as net primary productivity).

As shown in Figure 1, changes in the C cycle will affect air quality, via changes in the apportioning of carbon between CH_4 , CO_2 , CO, and NMHCs.

The DEEP GREEN climate model will formulate relationships between GHG emissions, GHG lifetime, radiative forcing, climate sensitivity, and temperature change. The climate model also will incorporate the effects of albedo, based on the work of Cai et al. (2016), Bright et al. (2016), Jones et al. (2013), and Cherubini et al. (2012), and will estimate regional temperature changes as well as global averages. Dr. Mark Jacobson,

an expert on climate and air-quality modeling, will consult on the development of this module. (Note that with other funding we already have begun work on the C-cycle module and the climate module.)

As indicated in Figure 1, changes in climate also will affect air quality, as discussed in the subsection “Air quality.”

Air-quality

DEEP GREEN will use a simple representation of the relationships between emissions and air quality. This representation will have three components: *i*) delineation of air-quality regions covering all countries in DEEP GREEN ; *ii*) updated source-receptor relationships derived from the Gaussian dispersion model in Delucchi and McCubbin (2007); and *iii*) simplified representations of ozone and aerosol chemistry. Dr. Jacobson will consult on the development of this module. (Note that with other funding we already have begun work on this component.)

As indicated in Figure 1, changes in climate can affect air quality. Climate change affects temperature, precipitation, wind speed, humidity, cloud cover, and other meteorological variables, which in turn affect photochemical reactions, deposition rates, natural emissions, and more (Weaver et al., 2009; Tagaris et al., 2009; Jacob and Winner, 2009; Post et al., 2012; Madaniyazi et al., 2015; Fiore et al., 2012, 2015; Zhang et al., 2017). Accordingly, we will develop simple relationships to account for the effect of climate change on air quality, such as the effect of higher temperatures on ozone air quality and aerosol formation.

Impacts of air pollution

For this module, we will update and build on our extensive earlier work on the impacts of air pollution in the United States (Delucchi et al., 2002; Delucchi, 2000; McCubbin and Delucchi, 1996, 1999; Murphy et al., 1999). For human health effects, we will start with the detailed health impact functions we created in McCubbin and Delucchi (1996) and for the original version of EPA’s health-effects BenMAP software (see RTI International, 2015, for current documentation of BenMAP-CE), and update them based on a thorough review and analysis of the literature, especially recent comprehensive studies of global impacts of air pollution (e.g., Cohen et al, 2017; Landrigan et al, 2017; Butt et al., 2017; Silva et al., 2016a; Pinkerton and Rom, 2014), studies focused on impacts in developing countries (e.g., Aragón et al., 2017; Barron and Torero, 2017; Gupta and Spears, 2017; Jack, 2017; Tian et al., 2017; Yergeau et al., 2017), and studies that estimate impacts by emission-source sector (e.g., Silva et al., 2016b; Lelieveld et al., 2015; Chambliss et al., 2014). Our health-impact functions will be continuous down to zero pollution levels, because recent studies (e.g., Di et al., 2017; Zhang, 2017), as well as our own prior research indicate that there is no effects threshold in exposure-response functions for ozone and particulate matter.

For impacts on agriculture, visibility, and other categories, we will perform simpler updates to our prior models (Murphy et al., 1999; Delucchi et al., 2002; Delucchi, 2000).⁵

For human mortality and morbidity impacts we will estimate disability-adjusted life-years (DALYs), which are the sum of years of life lost and years lost to disability. (See Cohen et al., 2017, for a recent example of estimating DALYs due to air pollution.)

Impacts of climate-change

DEEP GREEN will build upon the damage functions in the FUND model (Ackerman and Munitz, 2012; Waldhoff et al., 2014; Anthoff et al., 2009, 2011), which Dr. Anthoff has co-developed. We will extract the most important FUND damage functions (e.g., those leading to significant human mortality), and create reduced-form aggregations of the less important functions. Then we will expand beyond the current FUND model as follows:

- i) We will make general improvements using information from recent scientific compilations and reviews (IPCC 2013, 2014b; USGCRP, 2017, 2016; National Academies of Sciences, Engineering, and Medicine, 2017) and other research not covered in the compilations (e.g., Heal and Park, 2016; Auffhammer et al., 2017; Hsiang et al., 2017; Pizer, 2017).
- ii) In order to provide a unified impact-and-valuation framework, we will express human mortality and morbidity in terms of DALYs (as in the treatment of the impacts of air pollution).
- iii) As indicated in Figure 1, we will explicitly include the feedback of temperature change on air quality (see the brief discussion in the subsection on air quality).
- iv) As indicated in Figure 1, we will include the feedback of climate change to productivity, represented by GDP/capita. This is important because in a recent re-analysis of the social cost of carbon (SCC), Moore and Diaz (2015) find that incorporating the effect of climate change on the rate of economic growth – a feedback typically not included in estimates of the SCC – can dramatically increase the SCC to hundreds of dollars per ton and higher (see also Burke et al., 2015).
- v) We will calculate region-specific impacts based on region-specific temperature change rather than on global temperature change. This is important because poorer countries suffer disproportionate damages. For example, Harrington et al. (2016) find that for a given global emissions pattern, the poorest countries experience daily temperature extremes due to climate change earlier than do rich countries.

⁵ For a comparison of our earlier air-pollution-damage estimates with those of others, including Muller and Mendelsohn (2007), see Delucchi and McCubbin (2011).

Water quality and impacts of water pollution

For this component of DEEP GREEN, we will start with commonly used measures of water-quality impacts, such as eutrophication and aquatic ecotoxicity (van Zelm et al., 2009; Delucchi, 2010; Strujis et al., 2011; Kouloumpis et al., 2015; Hertwich et al., 2015; Berrill et al., 2016). We then will adapt USES-LCA 2.0, a multi-media fate, exposure and effects model, to derive health “damage” factors, expressed in DALYs, due to changes in steady-state exposure to a wide range of chemicals (van Zelm et al., 2009; 2015a, 2015b). We will compare these results with recent comprehensive studies of the global impacts of water pollution (Landrigan et al., 2017).

DEEP GREEN also will estimate the quantity and impacts of major spills of crude oil, routine leaks and spills of crude oil, leaks of petroleum from storage tanks, and urban runoff of oil products. DEEP GREEN will estimate leaks from underground storage tanks based on historical trends in cumulative releases not cleaned up (BTS, 2017a) and estimates of the average quantity per release. Oil spills will be estimated on the basis of historical trends in total gallons of oil spilled in navigable US waterways (BTS, 2017b), with a probabilistic treatment of extremely large spills such as the Deepwater Horizon blowout of 2010. Impacts and damages will be estimated based on our judgment, updating the simple analysis of Delucchi (2000) and Delucchi and McCubbin (2011).

Jobs

DEEP GREEN will have a simplified static model of changes in the total number of jobs associated with different decarbonization pathways, based on an improved version of the method documented in Jacobson et al. (2017). In Jacobson et al. (2017), the change in jobs was the product of *i*) an estimate of jobs per unit of some measure of energy output, and *ii*) a change in output. Jobs per unit of energy output for the US were based on data or models for the US, and jobs/unit for other countries were estimated relative to the US values, as a function of energy output and GDP/capita in each country relative to energy output and GDP/capita in the US. The method included “indirect jobs” (related to local employment and the supply chain), and “induced jobs” (arising from spending and re-investment or earnings from direct and indirect jobs), but did not account for changes in wages or changes in the prices of goods and services.

For DEEP GREEN, we will revise the Jacobson et al. (2017) calculation to ensure that estimates of the number of jobs are consistent with the estimated costs of all energy services.

Noise and impacts on aesthetics and biodiversity

DEEP GREEN will estimate noise and impacts on aesthetics and biodiversity from all energy systems, including but not limited to bio-energy systems (Gibon et al., 2017; Hastings, 2018), coal production, wind farms (Sokoloski et al., 2018; Pohl et al., 2018; Hui et al., 2018; Klain et al., 2018a, 2018b; Voltaire et al., 2017; Rand and Hoen, 2017; Krekel and Zerrahn, 2017; Katinas et al., 2016; Sovacool et al., 2016; Blane-Vidal and Schwartz, 2016; Mattman et al., 2016a; Crichton and Petrie, 2015; Ladenburg and Möller, 2011; Ladenburg and Dubgaard, 2009; Sovacool, 2009), large hydropower facilities (Mattman et al., 2016b), and small hydropower facilities (Pagnussatt et al., 2018;

Arabatzis and Myronidis, 2011). For transportation noise we will adapt a simplified version of the method in Delucchi and Hsu (1998), and estimate differences in noise impacts between internal-combustion-engine vehicles and battery-electric vehicles (see Delucchi [2000] and Delucchi and Lipman [2001] for an early estimate). We will develop simple noise-damage models for other significant sources of energy-system noise, based on reviews of the relevant literature (e.g., King and Murphy, 2016; Hays et al., 2017).

If time and resources permit, we also will estimate the impacts of building efficiency measures, such as additional insulation, on noise and indoor air quality (as in Jakob, 2006).

For general review of research on measuring and valuing natural and environmental amenities, see Schaeffer and Dissart (2018); Weber (2016), Polasky et al. (2015), and the United Nations et al. (2014a, 2014b).

Energy security

DEEP GREEN will estimate the externality “energy security” costs of the use of oil, including the use of oil in the “upstream” lifecycle of fuels. DEEP GREEN will include costs that are related to changes in oil consumption but are not reflected in oil prices (Leiby et al., 1997; Leiby, 2007): the construction, operating, and oil-holding costs of holding oil in reserves such as the US Strategic Petroleum Reserve (SPR); the costs of peacetime and wartime military expenditures related to defending oil interests, mainly in the Persian Gulf; and macro-economic price-shock costs related to importing oil. (Note that the costs of ground water and marine water polluted by oil are treated as water-pollution impacts, and that costs related to the transfer of producer surplus from US consumers to foreign oil producers are treated under “non-cost transfers.”) DEEP GREEN will treat these costs as follows:

- i) *The operating, capital, and oil-holding costs of holding oil in reserves.* The amount of oil stored in oil reserves as “insurance” against the effects of supply disruption may be presumed to be related, via political processes, to the amount of oil used in the economy or in major sectors of the economy such as transportation. DEEP GREEN will update the method presented in Delucchi (2007) and Delucchi and Murphy (2005), for all countries with significant holdings in oil reserves.
- ii) *Peacetime and wartime costs related to the use of oil from the Persian Gulf and other regions.* Changes in oil use arguably can affect the amount of government resources devoted to military operations in the Persian Gulf and other areas. (See Delucchi and Murphy, 2008a, for an in-depth discussion of the conceptual and methodological issues involved in estimating this cost for the US.) DEEP GREEN will update the estimates of Delucchi and Murphy (2008a), as informed by the analysis by Stern (2010), and expand the analysis to other countries.
- iii) *Short-term macroeconomic-adjustment losses of GDP due to oil-price shocks.* Jones et al. (2004) review research from 1996 to 2004 on the relationship between oil-price shocks and the US macroeconomy and conclude that: recessions that follow oil-price shocks are attributable mainly to oil-price shocks and could not have been prevented by alternative monetary policies; oil-price shocks can cause a considerable re-

allocation of labor; and the cumulative effect on GDP over a two-year period after a price shock is a contraction of -0.055% per 1.0% change in oil price. (This is represented in Figure 1 by the arrow from “energy security” to “GDP/capita”.) To estimate these macro-economic adjustment costs, we will implement within DEEP GREEN a revised version of the Oil Security Metrics Model (OSMM) (Greene and Leiby, 2006; Greene et al., 2014), the best available tool for quantifying the energy-security costs of oil use, and apply the revised OSMM to all countries where oil use is a significant fraction of GDP. To revise the OSMM we will use recent estimates of the “oil security” costs of US oil consumption (e.g., Brown and Huntington, 2013, 2015; Brown, 2018).

Because these external costs are due to the concentration of oil reserves in a few countries, and no other major energy resources (e.g., solar power or wind power) are as markedly geo-politically concentrated as are oil resources, we assume that there are no significant energy-security externalities associated with the use of other major energy resources.

GDP/capita

As shown in Figure 1, GDP/capita is an integral parameter in DEEP GREEN: it affects energy supply and demand, energy-system costs, job creation, energy-security costs, impact valuation, and the social discount rate, and is affected by air-pollution, climate change, water pollution, and energy-security impacts. This detailed integrated treatment ensures that all parameters that in reality are a function of GDP/capita are consistently estimated within DEEP GREEN.

The initial GDP/capita values and projections will be from the detailed documentation in Jacobson et al. (2015b, 2017). We will estimate GDP per capita in real US dollars, converted from each country’s currency on the basis of Purchasing Power Parity (PPP) (Deaton and Heston, 2010). For most countries, we will use the World Bank’s World Development Indicators of GDP per capita, in PPP-based constant year-2011 international dollars, for the period 1990 to 2015 (World Bank, 2016). We will fill in data gaps and project future GDP/capita as documented in Jacobson et al. (2017).

Impact valuation

For this component we will build on our previous detailed work with impact-valuation functions in Fund (Ackerman and Munitz, 2012; Waldhoff et al., 2014; Anthoff et al., 2011), BenMAP (RTI International, 2015) and the comprehensive social-cost analyses of McCubbin and Delucchi (1996, 1999), Murphy et al. (1999), Delucchi (2008, 2000), and Delucchi et al. (2002). We will update parameter values as appropriate, for example, by updating the value of agricultural output, in the case of valuing agricultural damages.

To value noise and impacts on aesthetics and biodiversity we will use methods in the literature including Mattman et al. (2016a, 2016b), Klain et al. (2018a), Krekel and Zerrahn (2017), Ladenburg and Möller (2011), Ladenburg and Dubgaard (2009), Desvouges et al. (2018), Hastings (2018), and Delucchi and Hsu (1998).

We will revise health-impact valuation functions to correspond to any changes in physical-impact functions (discussed above). We will estimate the value of DALYs due to mortality and morbidity, assuming that the value of a DALY has two components: one component related to lost productivity (GDP/capita), and one component that represents the universal constant utility of enjoying life and avoiding pain and suffering and hence is independent of relative wealth, productivity, or consumption.

To estimate the productivity component, we will follow Lindhjem and Navrud's (2015) meta-analysis of the value of statistical life (VOSL) across countries and assume that a portion of the value of a DALY for country *C* can be calculated as a function of the value for a reference country (e.g, the US) and the GDP/capita for country *C* relative to the GDP/capita for the reference country, where GDP/capita is expressed in terms of PPP. Then, we will follow the findings of Milligan et al. (2014) and Hammit and Robinson (2011) and assume that the GDP/capita elasticity of the VOSL (or DALY) is itself a function of the relative GDP/capita (based on PPP).

Because the impacts of climate change and air pollution disproportionately affect the poorest and most vulnerable populations (Nguyen and Marshall, 2018; IPCC, 2014b; Green, 2016; Harrington et al., 2016), it is important to properly account for utility-relevant differences between impacts on the poor and impacts on the rich. DEEP GREEN will do this by formalizing the standard economic assumption that a dollar's worth of damages to a poor person causes a greater loss of utility than does a dollar's worth of damage to a rich person.

The social discount rate

Because DEEP GREEN will estimate costs and benefits from the perspective of society, it will use a social discount rate to estimate the present value of all cost and benefit streams. The social discount rate will be derived from a basic "Ramsey" formula:

$$r = \delta + \eta \cdot g$$

where r is the social discount rate, δ is the so-called "pure rate of time preference," η is the absolute value of the elasticity of the marginal utility of consumption, and g is GDP/capita. We will estimate δ and η based on extensive review and analysis of the literature, which we have partially completed for a separate project. (For good overview discussions of the estimation of the social discount rate in the context of climate-change, see the IPCC [2014c] and the National Academies of Sciences, Engineering, and Medicine [2017].) We will estimate GDP/capita (g) as discussed above.

Energy-system capital and operating costs, system aging functions, and total lifetime costs

We will build on the work of Jacobson et al. (2015b, 2017) to estimate the full discounted lifetime costs of the major components of energy systems in each country. Lifetime cost estimates include all relevant resource costs: capital, fuel, operating and maintenance, replacement of major components, de-commissioning, and so on, over the life of the energy-using or energy-producing equipment. Because equipment lifetime is such an

important factor in the estimate of the total lifetime costs, we will develop explicit aging functions in which equipment lifetime is a function of time and the amount and pattern of energy usage. We will develop these aging functions for power generators, batteries (e.g., Uddin et al., 2018), and vehicles.

Jacobson et al. (2015b, 2017) provide detailed, fully documented estimates of the costs of electricity generation and efficiency-improvement measures; we will expand on these to include detailed estimates of the costs of electricity transmission and distribution and the costs of highway, rail, water, and air transportation. The estimates of the costs of electricity transmission and distribution will be consistent with the rudimentary supply-demand balancing algorithm mentioned above in the subsection on the energy system. To estimate costs for highway transportation we will use the Advanced Vehicle Cost and Energy-Use Model (AVCEM) (Delucchi, 2005a). AVCEM previously has been applied in Sun et al. (2010), Delucchi and Lipman (2010), Lipman and Delucchi (2006), and Delucchi and Lipman (2001), and is being expanded and updated with separate funding from USDOE. We will include all costs associated with transportation electrification scenarios, including for example scenarios involving very high-power vehicle recharging (see Burnham et al., 2017; Ahmed et al., 2017; Keyser et al., 2017; Meintz et al., 2017). Finally, we will account for cost reductions over time due to learning and cumulative production.

Note that we will not consider the so-called “rebound effect” of energy-efficiency improvements, whereby a lower cost of energy services, due to the efficiency improvements, induces additional energy use (Santarius and Soland, 2018; Wei and Liu, 2017; Gillingham et al., 2016). Although a hypothetically costless efficiency improvement can engender a relatively high rebound effect (above 50%; e.g., Wei and Liu, 2017), the long-run, economy-wide rebound effect of a real-world policy, which will have a number of costs and benefits beyond just improving efficiency, is highly uncertain and not necessarily even positive (Santarius and Soland, 2018; Gillingham et al., 2016).

Government program subsidies

The full social cost of energy systems can include government subsidies to energy production and use in the form of public expenditures on activities directly related to the energy system, such as regulation and research. Direct expenditures on government programs supporting energy production and use are a real *cost* of energy use if changes in energy production and use actually result in changes in government program expenditures, at least in the long run. Our estimates of these program-subsidy costs will draw on several sources: the work of Delucchi (2007) and Delucchi and Murphy (2005), who perform a comprehensive accounting of government expenditures in support of motor-vehicle and motor-fuel use in the US; the most recent review by the USEIA (2015) of federal financial subsidies in the US; and the recent reviews of global energy subsidies by Kojima and Koplow (2015), van Asselt and Kulovesi (2017), and Sovacool (2017). (Note that the cost of the holding oil in reserves and the cost of military expenditures related to oil use are classified here as “energy-security” costs.)

In the literature on “subsidies” related to energy use, certain kinds of tax subsidies (also known as “tax expenditures”) and price subsidies often are discussed along with direct

government-expenditure subsidies (e.g., Kojima and Koplow, 2015; Sovacool, 2017; USEIA, 2015). A tax subsidy to an entity is the difference between the taxes the entity actually paid and the taxes the entity would have paid if it had not received some “preferential” tax treatment. Using this definition, Delucchi and Murphy (2008b) estimate corporate-income-tax, sales-tax, property-tax, and personal-income-tax subsidies to motor-vehicle use. However, they emphasize that these kinds of tax subsidies do not correspond in any straightforward way to actual changes in social welfare, and so should not be added to government program subsidies in an analysis of total social costs and benefits. Therefore DEEP GREEN will not include tax subsidies.

By contrast, direct price subsidies do have a more straightforward impact on social welfare by creating so-called “deadweight” losses (Lucas, 2014). However, this is not relevant here because all estimates of energy-system costs in DEEP GREEN will exclude direct price subsidies.

Non-cost transfers

In most data sources, reported energy-system costs are based on market prices, such as the price of crude oil. However, price-times-quantity payments generally include producer surplus (PS), which is revenue in excess of the area under the long-run marginal-cost (LRMC) supply curve. Since the LRMC curve comprises all real resource costs, including normal returns on investments, PS is not an economic cost but rather a wealth *transfer* from consumers to producers. PS is especially large in the oil industry because many producers, especially those in the Middle East, have LRMCs well below the world price of oil.

Therefore, where PS is significant, DEEP GREEN will deduct estimates of PS from price-times-quantity estimates of energy-system cost. However, as discussed above, from a country-specific rather than a global perspective, PS accruing to foreign producers is a real cost to the consuming country, so in the country-perspective accounting, PS will not be deducted from price-times-quantity estimates.

PS will be estimated on the basis of LRMC curves for industries where PS is likely to be significant (see discussion, in the economic-system/price-effects section, of supply curves for the oil industry).

Total social lifetime cost/benefit (SCB) calculator

The DEEP GREEN SCB calculator will sum the discounted present value of all cost and impact streams: energy-system lifetime costs, external environmental and health-impact costs, energy-security costs, government program subsidies, and non-cost transfers. As mentioned above, the decarbonization scenarios will run through the year 2100, and will result in streams of costs and impacts that originate in each year through 2100. Each cost stream or impact stream originated in each year will be evaluated over the shorter of the stream’s effective lifetime or 1000 years. For example, energy-system costs will be evaluated through the end-of-life of each component, air-quality impacts will be evaluated over the period that the pollution has any effect, and climate-change impacts, which actually are indefinite, will be evaluated for 1000 years. Each cost and impact stream will be discounted back to the year it originated, and then all of these discounted

origination-year values will be further discounted to the overall base evaluation year of 2020. The year-2020 discounted values will be summed to produce the total discounted present-value cost.

DEEP GREEN also will report the components of the total discounted present-value cost, including year-by-year cost streams (undiscounted as well as discounted to origination year), and subtotals by impact category and region. As mentioned above, we will report results in physical-impacts units as well.

Scenario analysis and Robust Decision Making (RDM)

We will evaluate the results from DEEP GREEN within a “Robust Decision Making” (RDM) framework (McJeon et al., 2011; Hall et al., 2012; Kasprzyk et al., 2013). In this RDM approach, DEEP GREEN will be run many times to understand the relationships between model inputs and outputs and to identify the parameters that most influence the outcomes, with the ultimate objective of identifying the sets of inputs that generate low-cost and low-risk – that is, robust and sustainable – sets of results.

RESULTS FROM AND IMPACTS OF THE DEEP GREEN PROJECT

Expected results of the DEEP GREEN project

The DEEP GREEN project will have two main results:

- i) Estimation of the lifecycle environmental, health, and energy-security impacts and social costs and benefits of deep-decarbonization scenarios, with detailed understanding of the risks and benefits of slow-to-rapid transitions to 80% to 100% decarbonization, and identification of the most robust, sustainable, low-cost strategies. Specifically:
 - a) DEEP GREEN will provide a uniquely comprehensive, detailed, and internally consistent estimates of energy-system impacts on climate, air quality, water quality, and other criteria , in physical terms and full social-cost/benefit terms, for a wide range of transition pathways to various deep-decarbonization end-states, including – but not limited to – 100% decarbonization/zero-emission end-states.
 - b) With DEEP GREEN we will investigate a broad suite of energy, economic, and technological scenarios and test a wide range of parameter values and model specifications, in order to understand important uncertainties and sensitivities in energy-system transition scenarios.
 - c) We will use DEEP GREEN to identify the pathways that are the most “robust” – i.e., likely to produce environmentally and economically sustainable outcomes under a wide range of scenarios and model assumptions.

These results will be presented in research reports and journal articles.

- ii) Release of the publicly available, open-source DEEP GREEN modeling system. The modularity and comprehensive documentation of the DEEP GREEN modeling system will facilitate revisions and development by the scientific community. Our aim is to maintain DEEP GREEN as the premier, state-of-the art cost-benefit tool for estimating the environmental and economic impacts of deep-decarbonization scenarios.

Broader impacts of the DEEP GREEN project

DEEP GREEN will benefit scientists, policy makers, and members of the public interested in mitigating the environmental and economic impacts of energy use and developing robust, sustainable energy systems.

“Sustainability” comprises environmental, social, and economic aspects, where the environmental criteria include ecosystem services, air quality and water quality; the social criteria include human health and resource security; and the economic criteria include jobs and costs (USEPA, 2017). Deep-decarbonization scenarios – especially those that involve transitions to 100% WWS systems (Jacobson, 2009) – can promote global sustainability along multiple dimensions by improving air quality and water quality, mitigating climate change, protecting human health, stimulating job growth, enhancing energy security, and delivering energy at reasonable cost. DEEP GREEN will thoroughly evaluate a wide range of deep-decarbonization transition strategies and energy-system end-states with respect to all pertinent sustainability criteria.

Because DEEP GREEN will be the first modeling system to integrate the full set of elements needed for a comprehensive, detailed, internally consistent analysis of the lifecycle, multi-media, multi-pollutant estimation of the environmental, health, and energy-security impacts and social costs and benefits of deep-decarbonization scenarios (see “Overview” and Figure 1), DEEP GREEN will be able to:

- i) examine, within a unified framework, the importance of a uniquely wide range of key factors (e.g., the use of energy to make materials for solar energy systems; the effects of energy-price changes on land use and resultant changes in albedo and climate; the effects of ammonia emissions on nitrate aerosol formation and on other aspects of the N and climate cycles; the effects of climate change on air pollution; the effects of climate on GDP/capita; and the effects of changes in GDP/capita on parameters such as the statistical value of life, wages, and jobs); and
- ii) provide comprehensive evaluations of critical but generally under-explored questions, such as: *a)* the costs and benefits of rapid vs. slow phase-in of renewable energy systems, where the benefits are earlier and faster mitigation of climate-change, air-pollution, and water-quality impacts, and the costs are earlier and more extensive investments in less-advanced infrastructure and technology (see Liu et al. [2017] for an analysis of this kind of tradeoff in the case of replacing residential lighting) ; *b)* the mix of energy sources and technologies (e.g., batteries, hydrogen fuel cells, advanced biofuels) that provides the greatest net social benefits in different transportation sectors; *c)* the advantages and disadvantages of linking countries and regions into super energy grids; *d)* the system-wide benefits, costs, and risks of having varying levels of nuclear power; and *e)* the full costs and benefits

of using biofuels, including the costs of foregoing more socially beneficial uses of land.

By elucidating the important drivers and tradeoffs of a wide range of decarbonization scenarios, results from DEEP GREEN can help policy makers, researchers, and other stakeholders develop scientifically sound, sustainable energy strategies that offer relatively large social benefits (better air quality, less rapid and extreme climate change, greater energy security, and so on) with relatively low costs and risks.

The DEEP GREEN project also will mobilize a multi-disciplinary team and build an interdisciplinary knowledge base, publish numerous articles in the scientific and policy literature, and produce an open-source version of the DEEP GREEN modeling system for continued development by the scientific community.

MODEL VALIDATION AND DATA MANAGEMENT

Model validation

As discussed in the section “Data management plan,” the DEEP GREEN model will be developed in the programming language Python. Model code will be checked and verified as written, by unit-testing stand-alone sections of code to verify that they produce the intended results. To ensure that the assumptions and algorithms in the DEEP GREEN model component produce reasonable results, we will run three kinds of validation checks:

- i) compare output with known benchmarks; e.g., the data points used to build the functions in the model;
- ii) evaluate the reasonableness of results outside of the benchmark data range on the basis of theoretical and empirical considerations; and
- iii) compare DEEP GREEN output with results from other models designed for substantially the same purpose and specified in the same way.

Data management plan

DEEP GREEN will be an open-source modeling system built using existing, publicly available data from sources such as the US Department of Energy, the US EPA, the US Bureau of the Census, US National Laboratories, the International Energy Agency, the IPCC, the World Bank, the United Nations Environment Program, published papers and reports, other open-source modeling efforts (e.g., GCAM), and so on. No proprietary data or proprietary software will be used.

Given this, the DEEP GREEN project requires:

- protocols and a platform for accessing and sharing data and other materials among team members during the development of DEEP GREEN;
- an open-source platform for development of the modeling system;
- a publicly accessible project web site for posting project data and results; and
- plans for long-term archiving of project data, results, and publications.

Protocols and a Platform for Accessing and Sharing Data and Other Materials among Team Members During the Development of DEEP GREEN. During the active phase of the project, the DEEP GREEN project team staff will have access to working data sets, research reports, interim documentation, project communications, and intermediate processed results as they are uploaded by team members into a project folder stored in Box. UC Berkeley licenses an enterprise version of Box, with FERPA and US-EU Safe Harbor protections, as a cloud-based collaboration service with unlimited storage provided free for research projects (<https://berkeley.app.box.com/files>). Group permissions will be set up in Box so that the files can be accessed only by the research team.

Open-source Software Development Platform. DEEP GREEN model code will be developed and maintained in the open-source software-development platform github (<https://github.com/open-source>), which will contain all working data files, working code, and supporting code documentation. We will use the open-source language Python. The github platform will be for working model development only; non-code-related file-sharing among team members will be handled through Box (see above), and dissemination of interim results, documentation, and reports will be done through the project web site (see below). We aim to use the Creative Commons Attribution license (CC-BY-4.0) to facilitate sharing and reuse of our software.

Publicly Accessible Project Web Site for Posting Project Data and Results. In-progress results, working documentation, some data sets, and project-overview materials will be published on the DEEP GREEN project web site, which will be hosted on the Open Berkeley platform (<https://open.berkeley.edu>) with the attribution license mentioned above. These published materials will provide summary information about the project and results. Links to archived data and publications will be provided (see next section). Papers published as a result of this research will be made available through UC Berkeley's EScholarship, an open-access publishing platform for UC researchers to disseminate the full range of their scholarship.

Plans for Long-term Archiving of Project Data, Results, and Publications. Upon conclusion of the project and as the completed results, data sets, documentation, and publications are released, all final archivable materials will be published in DASH, a data archiving and sharing solution developed by the California Digital Library (CDL) (<http://www.cdlib.org>) and implemented at UC Berkeley (<https://dash.berkeley.edu/stash>). The final archival package will be assigned a DOI; any datasets archived separately per publisher requirements will be assigned separate DOIs. A readme file will be included with the materials to provide context and documentation. Those interested will also be pointed to final publications and to the

project web site (see previous section) where additional information about the project and its data will be kept.

DASH will provide a long-term access point to the project's data sets and results. In addition, data will be backed up in the university's long-term archive which permits the material to be permanently held in UC's Merritt repository (<https://merritt.cdlib.org>). Merritt provides a secure environment for long-term preservation of and access to the university's digital assets. Merritt uses redundancy and continually runs fixity checks to avoid any possible corruption and loss of data. Data in Merritt is backed up in two different data centers: the San Diego Supercomputer Center's Cloud Storage Service and UCLA's Cloud Archival Storage Service.

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FIGURE 1. THE DEEP GREEN MODELING SYSTEM

